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Author(s): Batha, Steven H.; Broughton, David Paul; Huang, Chengkun; Reinovsky, Robert Emil; Schmidt, Thomas Robert Jr.; Wolfe, Bradley Thomas; Wong, Chun-Shang; Wyatt, Benjamin Ludwigson

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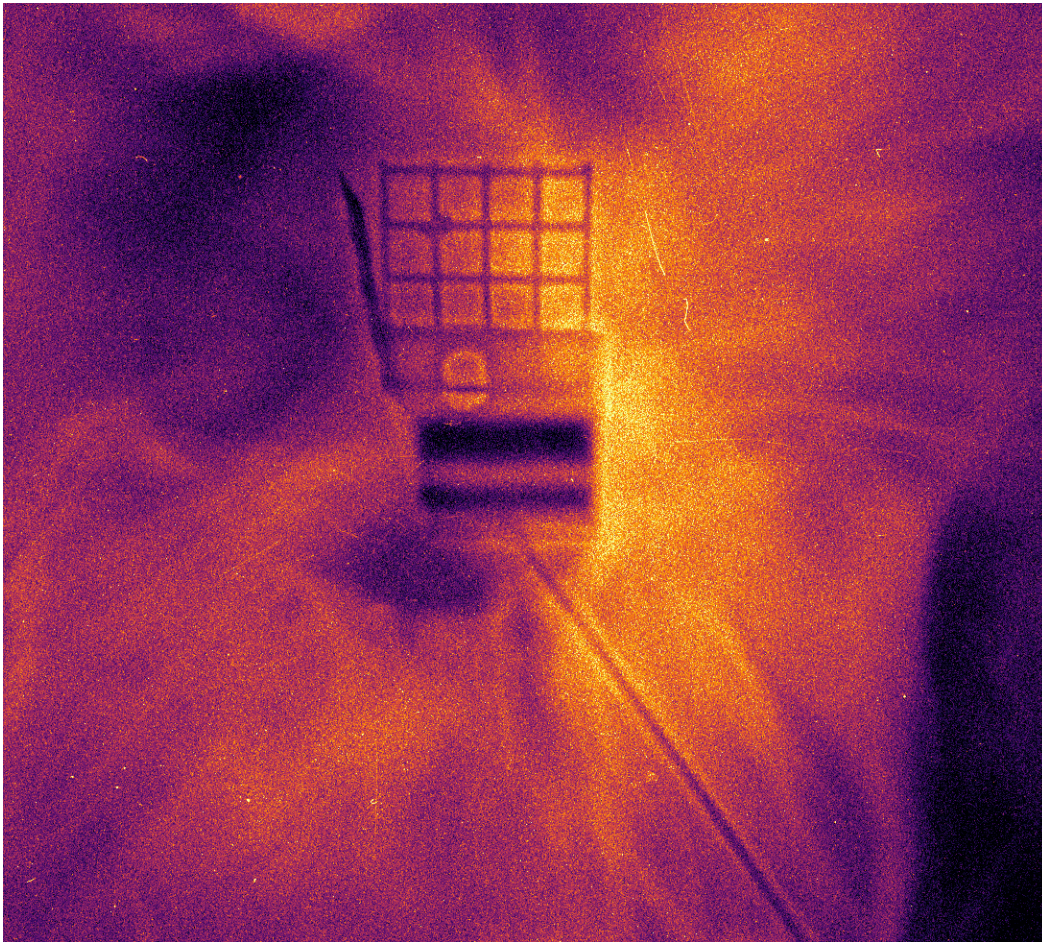


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Multi-Probe 22A: Post shot Data and Analysis

March 9, 2022

S. H. Batha, D. P. Broughton, C. -K. Huang, R. E. Reinovsky, T. R. Schmidt, B. Wolfe,
C.-S. Wong, and B. L. Wyatt



Abstract

The Multi-Probe 22A experiments took place on the Omega EP laser in March 2022. The goal was to discover issues with simultaneous x-ray and proton radiography of static and dynamic test objects. The x-ray and proton probes were generated by short-pulse laser-matter interactions. Significant crosstalk between the proton beam and x-ray detector was observed. Several static radiographs were made, including a set of proton images made with different laser energies. No dynamic objects were radiographed.

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Goals

The experiment had four goals.

1. Radiograph a static test object with an x-ray probe.
2. Radiograph a static object with a proton probe.
3. Radiograph a dynamic test object with an x-ray probe.
4. Radiograph a dynamic object with a proton probe.

Results

Radiographs using x rays and protons separately were obtained of static objects. No simultaneous radiographs were obtained by both probes. No dynamic objects were radiographed. Crosstalk between the proton target and x-ray detectors was observed.

Summary of shot day

Day Log

The first proton-only shot produced tremendous saturation of the x-ray image pack that was located almost 90 degrees relative to the proton beam. We increased filtering on the x-ray pack in incremental steps until no background x-rays were detected with 6 mm of Cu filters. Concurrent with the increased filtering, the energy of the laser driving the proton beam was also decreased from 500 J to 250 J, 125 J, and 60 J.

The starting point for the proton beam shots was the configuration used in MP 21B. The x-rays were driven with a 20 J, 0.7 ps pulse for the first part of the day. Eventually it was realized that the MP 20B best results were obtained with a 5-ps pulse, so the pulse length was increased. The energy was also subsequently reduced.

The static object consisted of a CH block with three holes of different sizes drilled into it. Three W wires were laid across the back and a Cu grid was placed on top. The holes were aligned with the proton beam and the wires were along the x-ray beam direction, perpendicular to the holes.

The image quality of both the x-ray and proton images appeared to be less than in MP 20B or MP 21B. However, it must be taken into consideration that the x-ray image plates were scanned at a lower resolution for these measurements when assessing the x-ray images.

Simultaneous probes were abandoned after three shots as the background on the x-ray image plates was too high. This enabled a faster shot rate.

No dynamic radiographs were attempted.

The last proton-only shot had no static test object so this is a “flat field” of the proton beam.

No dynamic test objects were shot. The design of these targets needs to be reconsidered due to the very oblique angles involved. Perhaps a hohlraum target should be used in the future.

Shot List

Shot #	Type	X-ray Beam Delay (ns)	RID	Note
36435	Proton	N/A	86417	Laser warms up; Proton half energy
36436	X Ray	N/A	86418	Laser warms up; X-ray half energy
36437	Proton	N/A	85832	Proton full energy
36438	Both	BL1 +2	85690	Simultaneous radiographs; vary IP filtering
36439	Both	BL2 +2	86419	Simultaneous radiographs; vary IP filtering
36440	Both	0	86420	Simultaneous radiographs; vary IP filtering
36441	X Ray	N/A	85831	Increase x ray pulse to 5 ps
36442	Proton	N/A	86619	Decreasing proton energy, increasing IP filtering
36443	X Ray	N/A	86621	Reduce x-ray energy to 15 J
36444	Proton	N/A	86620	Background emission flat field; no static object

Laser performance on proton shots

Shot #	Energy (J)	Focal spot, R_{80} (μm)	Pulse Length (ps)	Proton Intensity (W/cm^2)	a_0
36435	263	17.6	0.7	3.09×10^{19}	4.97
36436					
36437	492.3	15.7	0.7	7.27×10^{19}	7.63
36438	496.6	16.2	0.7	6.88×10^{19}	7.43
36439	241	15.4	0.7	3.70×10^{19}	5.44
36440	115.7	16.3	0.7	1.58×10^{19}	3.56
36441					
36442	60	15.8	0.7	8.74×10^{18}	2.65
36443					
36444	56	15.8	0.7	8.16×10^{18}	2.56

Laser performance on x-ray shots

Shot #	Energy (J)	Focal spot, R₈₀ (μm)	Pulse Length (ps)	Intensity (W/cm²)	a₀
36435					
36436	20.2	18.3	0.7	2.19×10¹⁸	1.33
36437					
36438	20.1	17.9	0.7	2.28×10¹⁸	1.35
36439	20.1	17.3	0.7	2.44×10¹⁸	1.40
36440	19.8	17.0	0.7	2.49×10¹⁸	1.41
36441	20.0	17.2	5.0	3.44×10¹⁷	0.53
36442					
36443	15.0	17.1	5.0	2.61×10¹⁷	0.46

Targets

Target modifications

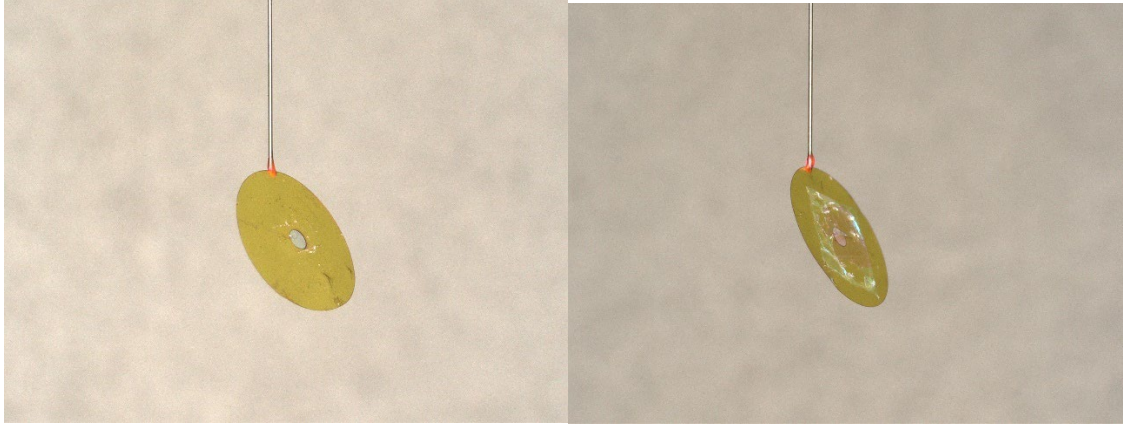
The only change was that Cu grids were used in place of Au ones. The dimensions were the same for the Cu as specified for the Au grids.

Targets used

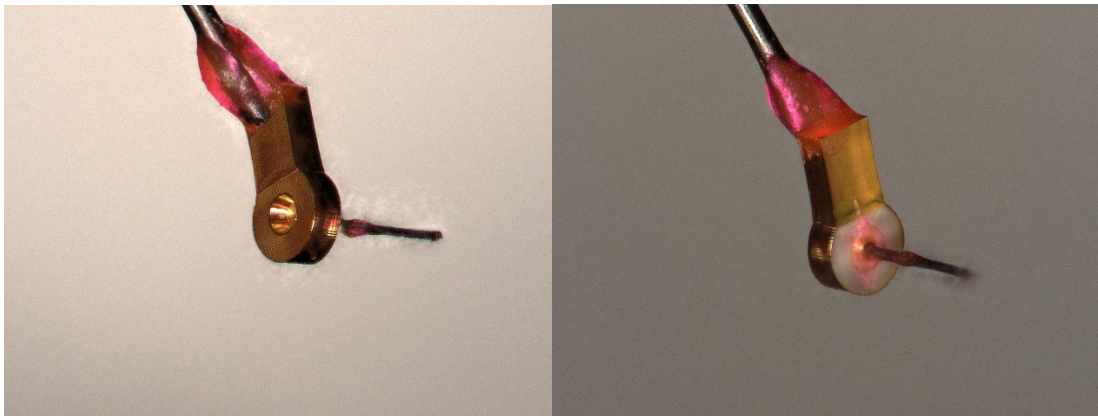
Shot #	X-Ray Target #	Proton Target #	Static Target #
36435	N/A	12	29
36436	34	N/A	24
36437	N/A	11	291
36438	31	15	20
36439	38	18	25
36440	41	13	28
36441	36	N/A	21
36442	N/A	14	22
36443	33	N/A	26
36444	N/A	19	N/A
No Dynamic Test Object targets were used			

Sample Target Pictures

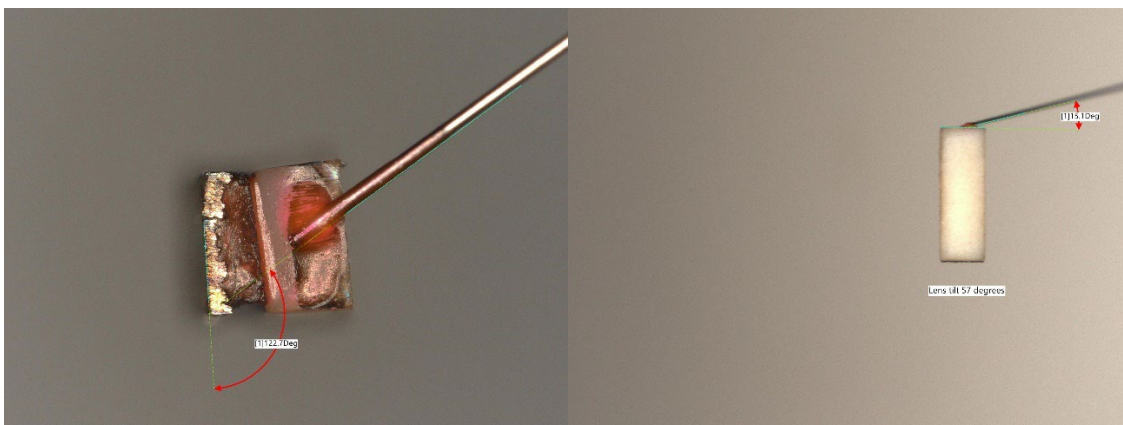
Example pictures of proton test object



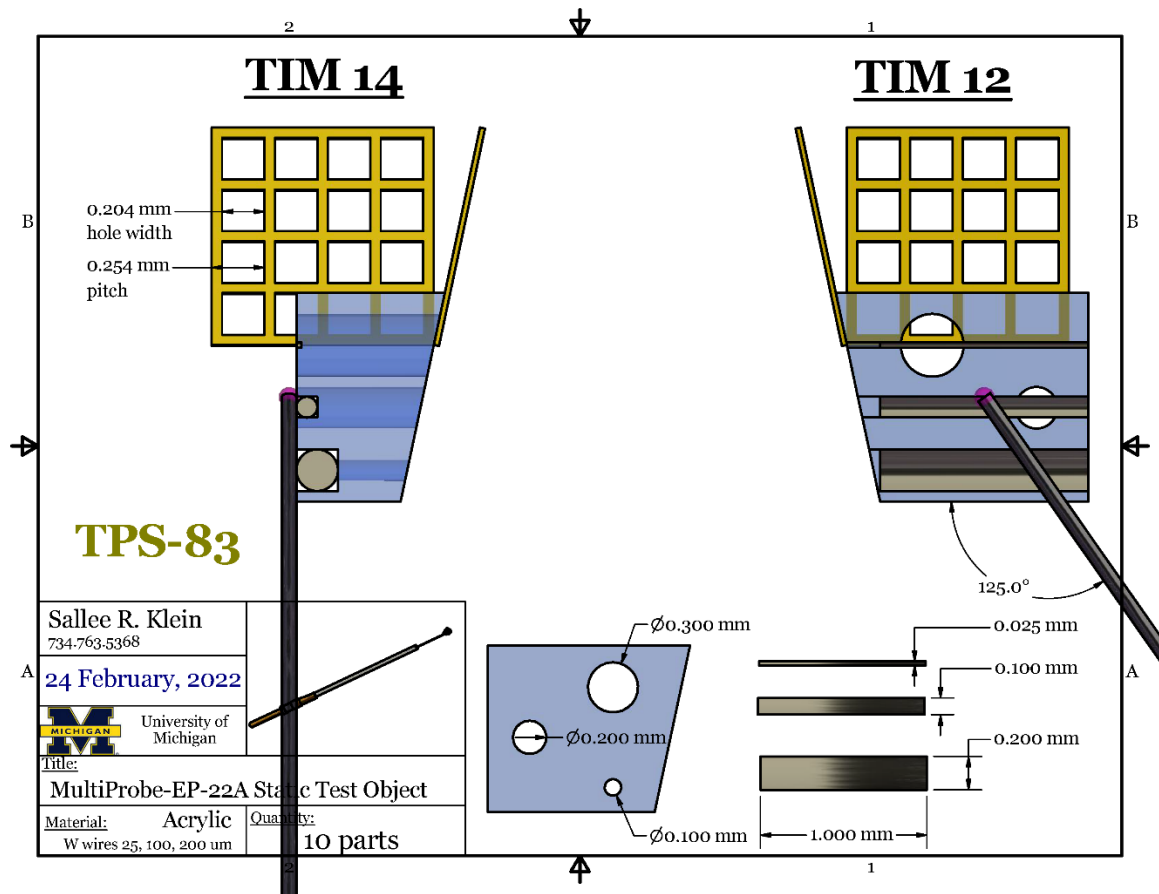
Example pictures of x-ray target



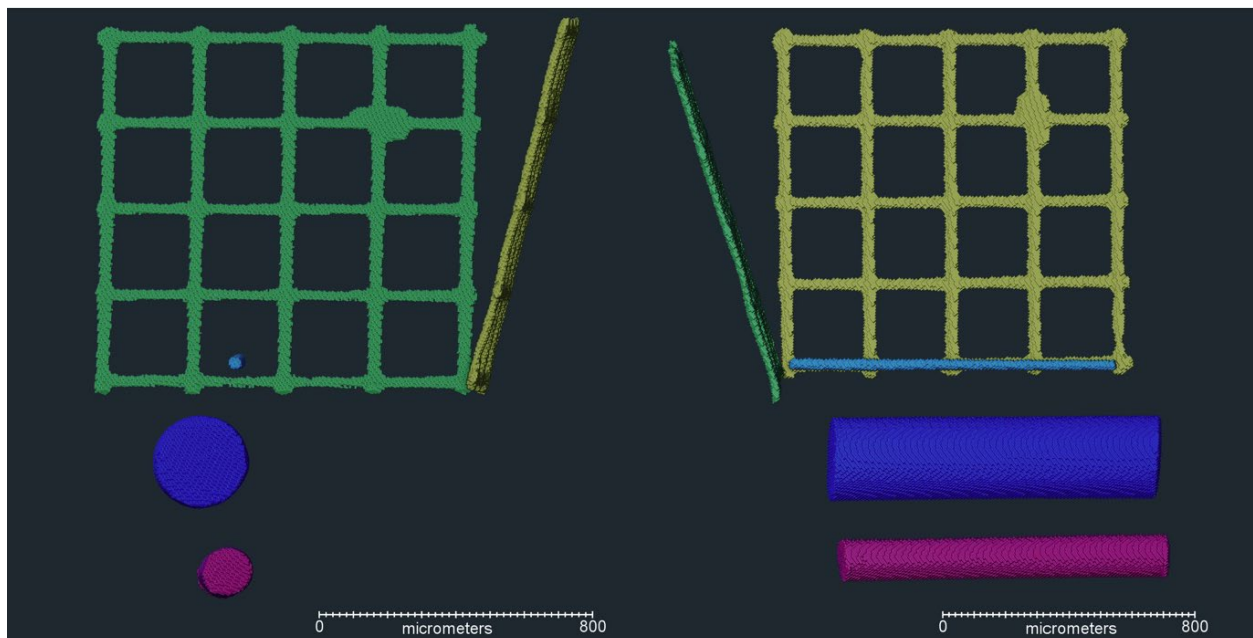
Example pictures of dynamic test object



Static test object
Engineering drawing



CT scan of static test object



Post-shot comments on static target

- Two leftover targets were scanned on the nano-CT in MST-7
- These samples were difficult to image with the high Z and low Z components.
- The data was reconstructed twice, once optimized for high Z and again for low Z.
- Holes were difficult to see, but some issues were noted.
- Were assembled with the grids on the opposite side of the CH from the drawing.

Diagnostics

Instruments Used

Diagnostics Table				
TIM	A 85831	B 85832	C 85690	D 85833
13		Proton Package	Proton Package	Proton Package
14	DUAL NTA RCF + IP	DUAL NTA RCF + IP	DUAL NTA RCF + IP	DUAL NTA RCF + IP
TPS 7	X Ray Package		X Ray Package	X Ray Package
TPS 83	Static Test Object	Static Test Object	Static Test Object	Dynamic Test Object
Fixed	A 85831	B 85832	C 85690	D 85833
25	BMXS-25	BMXS-25	BMXS-25	BMXS-25
55	BMXS-55	BMXS-55	BMXS-55	BMXS-55

Definitive information about IP pack, RCF film pack, and step wedges

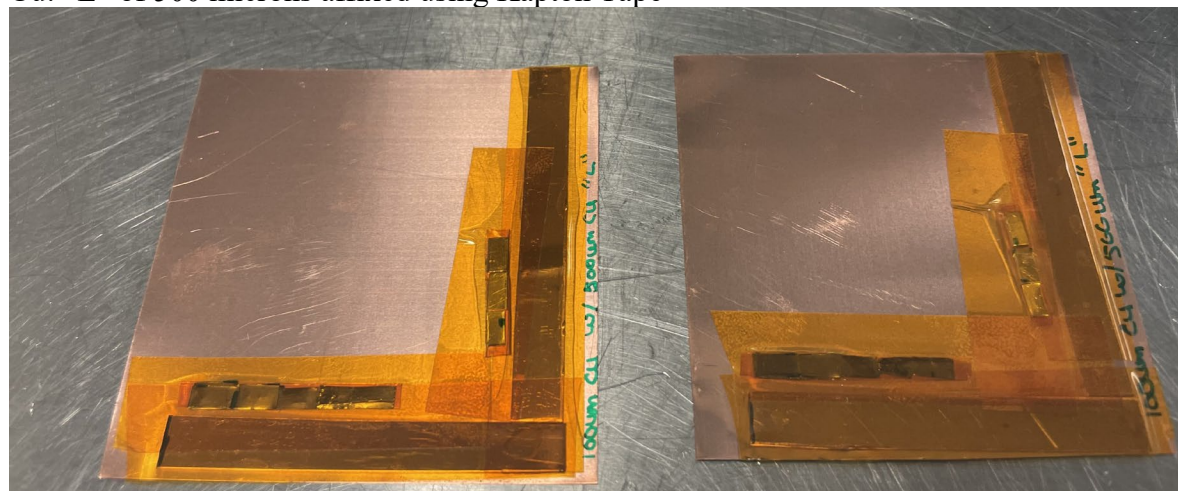
X-ray Image Plate Pack:

Step wedges used on shots 36435-36443:

Al: 100, 500, 1000 microns (vertical orientation in image below)

Ta: 7.5, 10, 50, 350, 400 microns (horizontal orientation in image below)

Cu: "L" of 500 microns affixed using Kapton Tape



Step Wedge used on Shot 36444:

Consisted of Cu foil, with major thicknesses of 200,700, 1200 microns, with a 1000 micron strip on the side, creating total thicknesses of 1200, 1700, and 2200 microns.

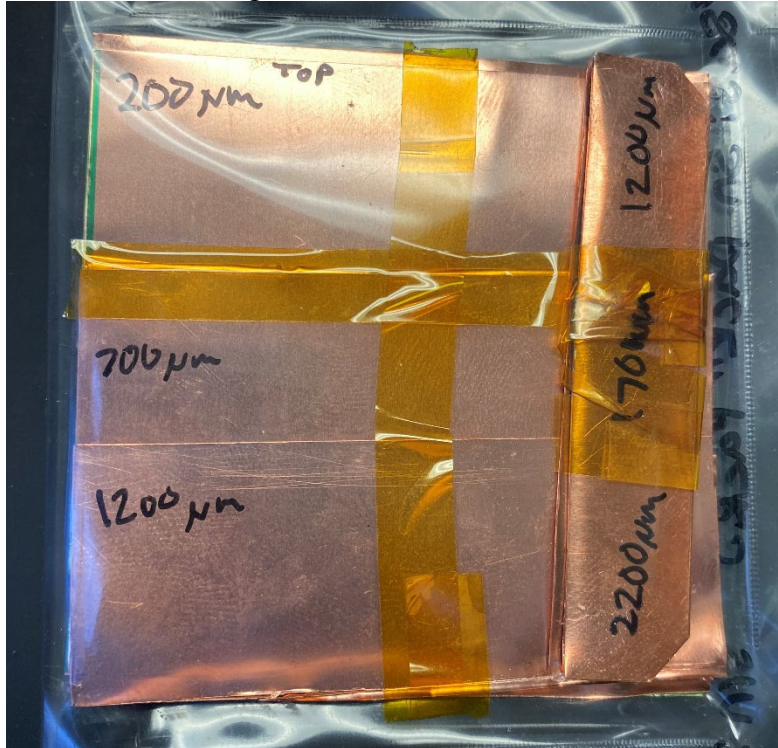
**Image Plate Pack stack filtering (inter-plate filtering), CONSTANT FOR ALL SHOTS:**

Image plate #	Material	Thickness [μm]
Plate 2	Cu	50
Plate 3	Cu	50
Plate 4	Cu	50
Plate 5	Cu	50

Front facing filter on X-ray IP pack for each shot (including Al and Ta step wedge, and Cu “L”):

Shot #	Material	Thickness [μm]
36435	Cu	200
36436	Cu	200
36437	Cu	200
36438	Cu	200
36439	Cu	3000
36440	Cu	1000 + 1000
36441	Cu	200
36442	Cu	6000
36443	Cu	200
36444	Cu	Step Wedge

Radio Chromic Film (RCF) Filter Pack

Layer	Material	Layer Thickness (microns)	Minimum Proton Energy (MeV)
1	Cu	50	
2	HDV2		3.9
3	Sn	500	
4	HDV2		13.1
5	Sn	500	
6	HDV2		18.9
7	Sn	500	
8	HDV2		23.7
9	Sn	500	
10	HDV2		28.0
11	Sn	500	
12	HDV2		31.8
13	Sn	500	
14	HDV2		35.3
15	Sn	1000	
16	HDV2		41.5
17	Sn	1000	
18	HDV2		47.1
19	Sn	1000	
20	HDV2		52.3
21	Sn	1000	
22	MDV3		57.4
23	Sn	1500	
24	MDV3		64.3
25	Sn	1000	
26	MDV3		68.8
27	Sn	1000	
28	MDV3		73.0

The above RCF Filter pack was used on shot day. The intention was to have the first layer of material be 100 μm Sn; however, it had to be replaced by the Cu filter.

X-Ray image plate filter pack

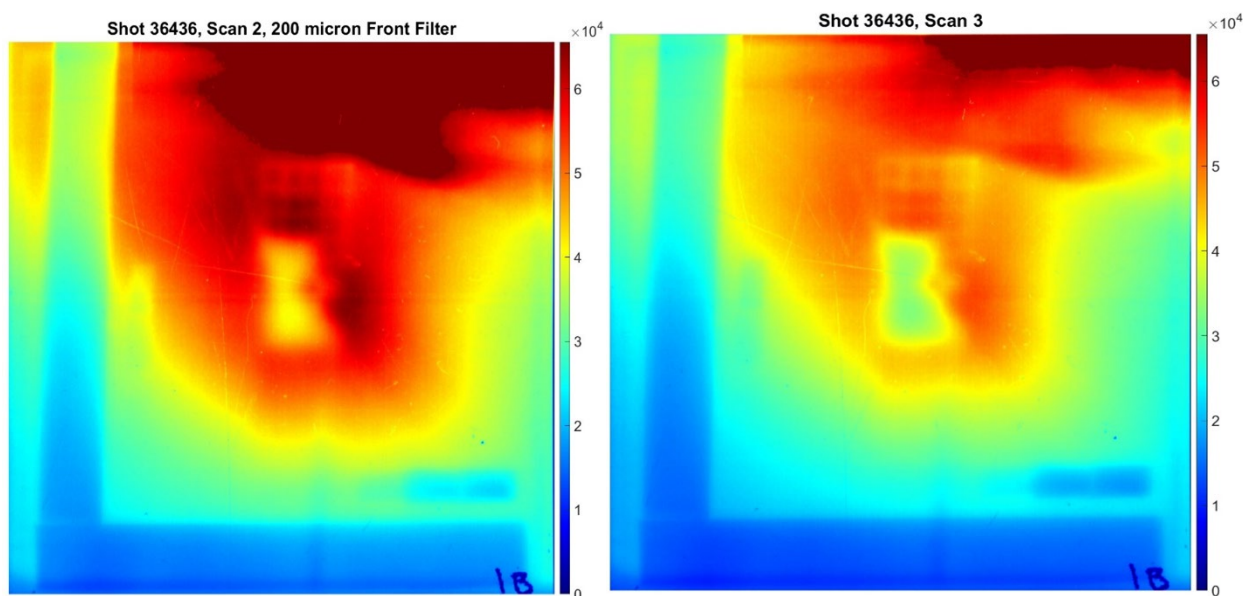
The x rays were recorded by a stack of image plates with filters as listed below. Scanning of the image plates started with a 25 μm aperture. With the extreme saturation (31 scans did not yield an unsaturated image), the aperture was increased to 100 μm after the first shot to decrease the scan time. This affects the ability to discern the thin wires on all the x-ray images.

Layer	IP #	Material	Thickness (mm)	Total Thickness (mm)
1		Cu	0.2	0.1
2	1	SR-IP	0.5	0.6
3		Cu	0.05	0.65
4	2	SR-IP	0.5	1.15
5		Cu	0.05	1.2
6	3	SR-IP	0.5	1.7
7		Cu	0.05	1.75
8	4	SR-IP	0.5	2.25
9		Cu	0.05	2.3
10	5	SR-IP	0.5	2.8
11		Cu	0.5	3.3

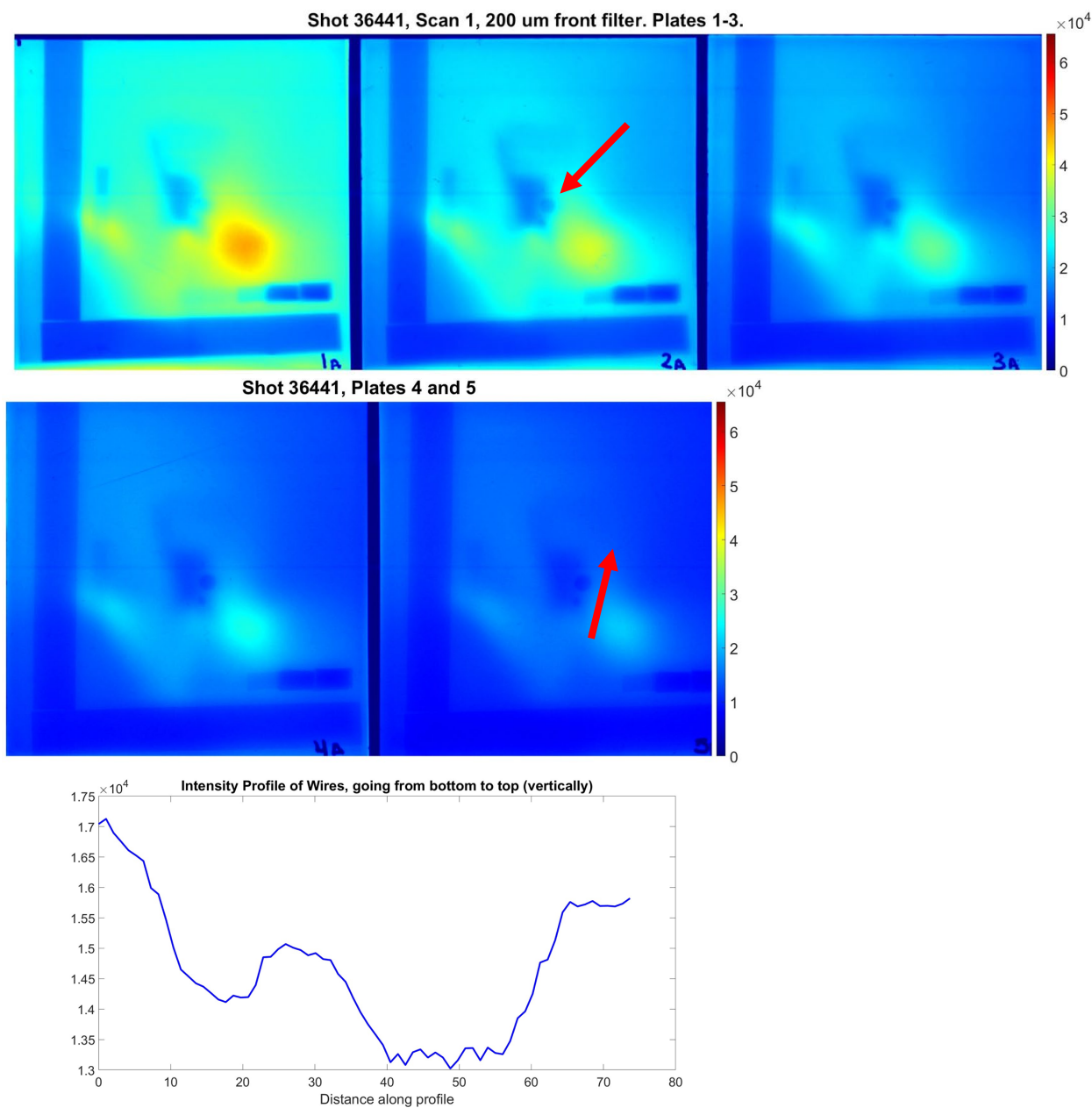
Diagnostic Measurements

X-Ray Images

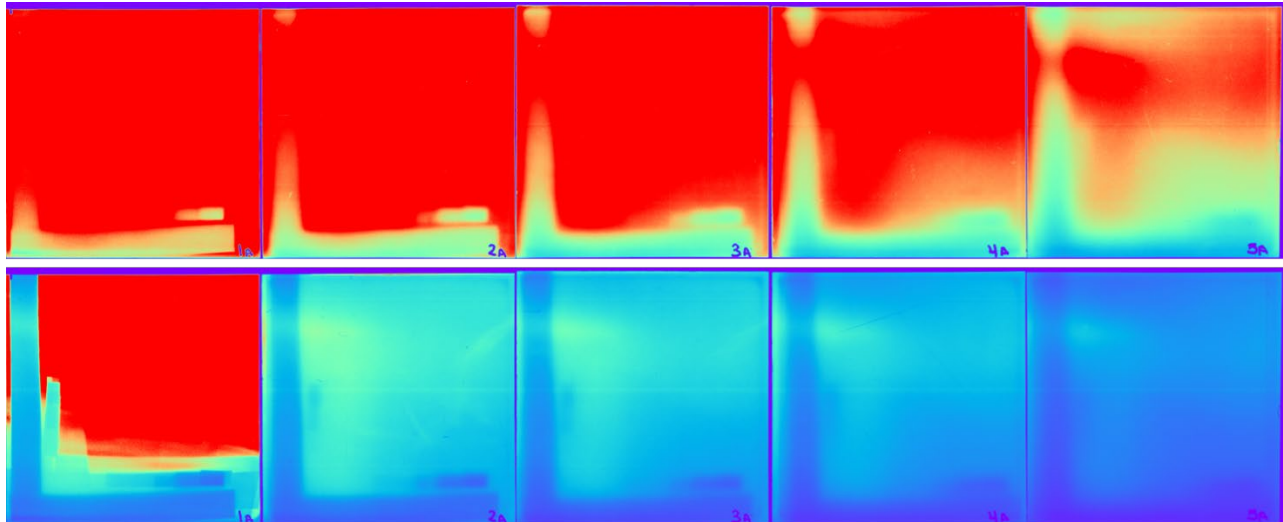
The static object grid was best resolved on Shot 36436 (Type A, 20J, 0.7ps). However, two factors must be considered. The Cu wire diameter is 50 μm and all scans after shot 36436 were at a resolution of 100 μm . Attenuation in the wire is low (<38%) for photons above 30 keV and the first 0.2 mm Cu filter on the IP stack attenuates over 85% of photons at and below 30 keV.



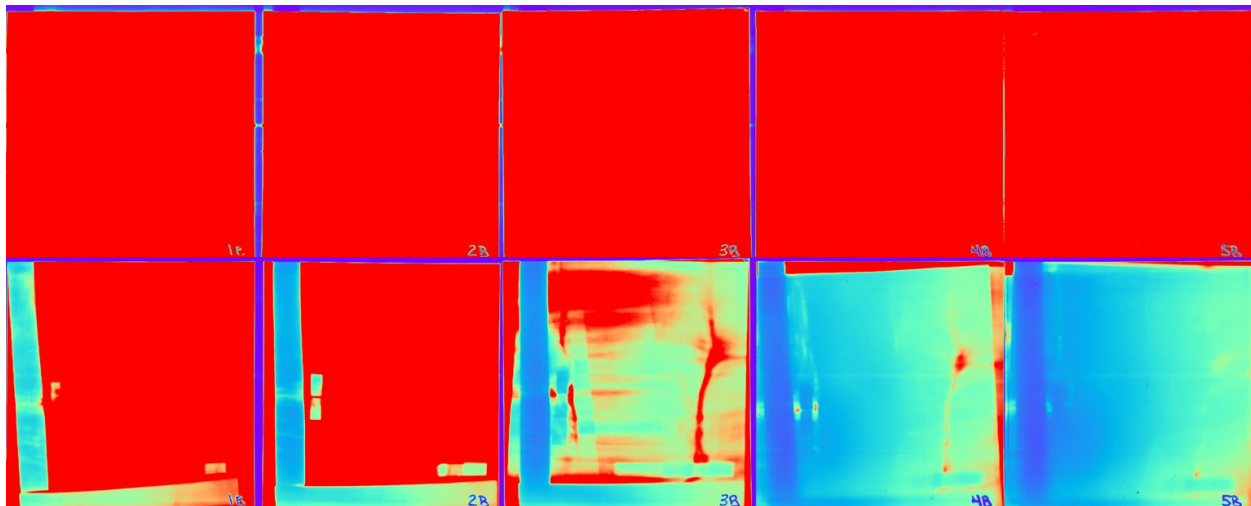
The two largest wires could be observed as well with x-ray radiography on shot 36441 (Type A, 20 J, 5 ps) as shown in the following images. An x-ray intensity profile with local minima arising from each of the wires is also provided. The x-ray source size is $<100\text{ }\mu\text{m}$ since the $100\text{ }\mu\text{m}$ diameter wire is clearly visible. The $25\text{ }\mu\text{m}$ diameter wire is not visible given the $100\text{ }\mu\text{m}$ scanning resolution. The apparent hot spot in the 36441 may be due to electrons as this feature was not present on September 2020 shot day using the MIFEDS to deflect electrons. This suggests that electron deflection is likely required to achieve the best possible radiograph quality with these CPC cone and Ta wire targets.



Next are examples of x-ray imaging of the step wedge with image plates. The top row is for shot 36435 IP scan #2 and the bottom row is for scan #7. Note that the repeated scans improved the contrast in the images until the step wedge features can be easily distinguished.

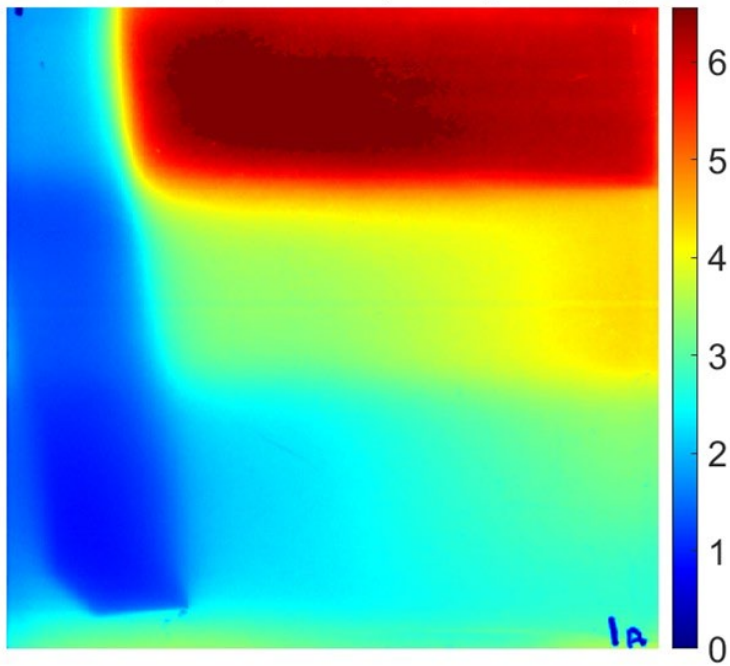


In some cases, however, artifacts in the images were observed after many scans. Below are images of scan #1 and scan #31 for shot 36438. While the contrast was improved, some features in the images appear to be unphysical.

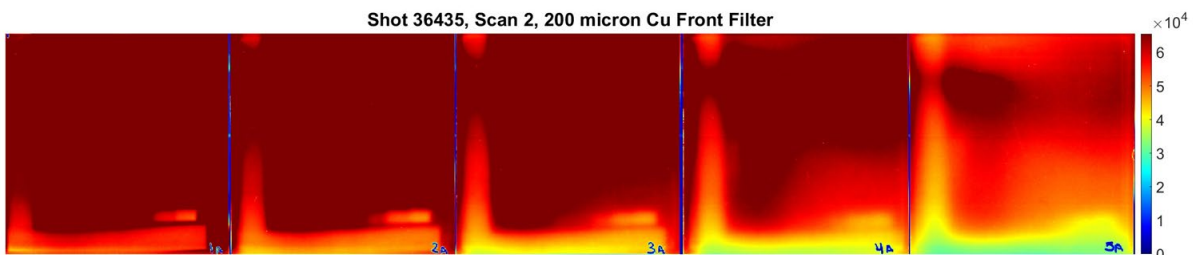


The thick, coarse step wedge described earlier allowed for measurements to be obtained without the extreme saturation, as shown in the next image.

Shot 36444, Scan 3, 'Step Wedge' $\times 10^4$



Significant cross talk between the proton source and the x-ray image plate stacks were observed on the proton only shots. Below are image plate scans (scan #2) from shot 36435 (proton only, Type B, 263 J), where the image plates were located perpendicular to the axis for proton beam generation. The x-ray intensities for this proton-only shot were comparable, if not larger, than those for some of the x-ray shots. This may in part be due to the configuration of Omega EP lasers, where separation between the proton target and x-ray image plates is less than that of the x-ray target and the image plates.



The substantial cross talk between the proton source and the x-ray detectors is an important obstacle that needs to be overcome to field simultaneous proton and x-ray beams. Potential strategies to reduce the cross talk include adding shielding between the proton pack and image plates or optimizing the geometry between the beams and detectors based on the angular dependence of the x-rays emitted from the proton pack. Alternatively, time gated detectors could be used to ensure x-rays are only measured immediately following the x-ray driving laser pulse.

BMSX X-Ray Spectrum Data

X-ray spectra were measured using the bremsstrahlung x-ray spectrometer (BMXS) during the independent and nearly simultaneous x-ray and proton radiographs. The BMXS is positioned

orthogonally to the lasers driving both x-ray and proton sources to give a measure of the spectrum at 90 degrees. Spectra reported here may be revised as analysis is improved.

The x-ray spectra measured using the Ta wire target and CPC cone all show a low energy peak at ~ 30 keV, with smaller peaks due to the respective k_{α} and k_{β} emissions of 57 and 65 keV. Comparing the 15 J and 20 J x-ray spectra at 5 ps shows that increasing energy increases overall flux, particularly above 100 keV. Shortening pulse duration from 5ps to 0.7 ps further enhances high energy flux.

The simulated spectrum in Fig. 1 was used as the input guess spectrum for the x-ray only shots. A Monte Carlo MCNP 6.2 simulation was conducted using an array of initial electron spectra defined within 10-degree angular bins based on results of 2D PIC simulations conducted using the SMILEI code.

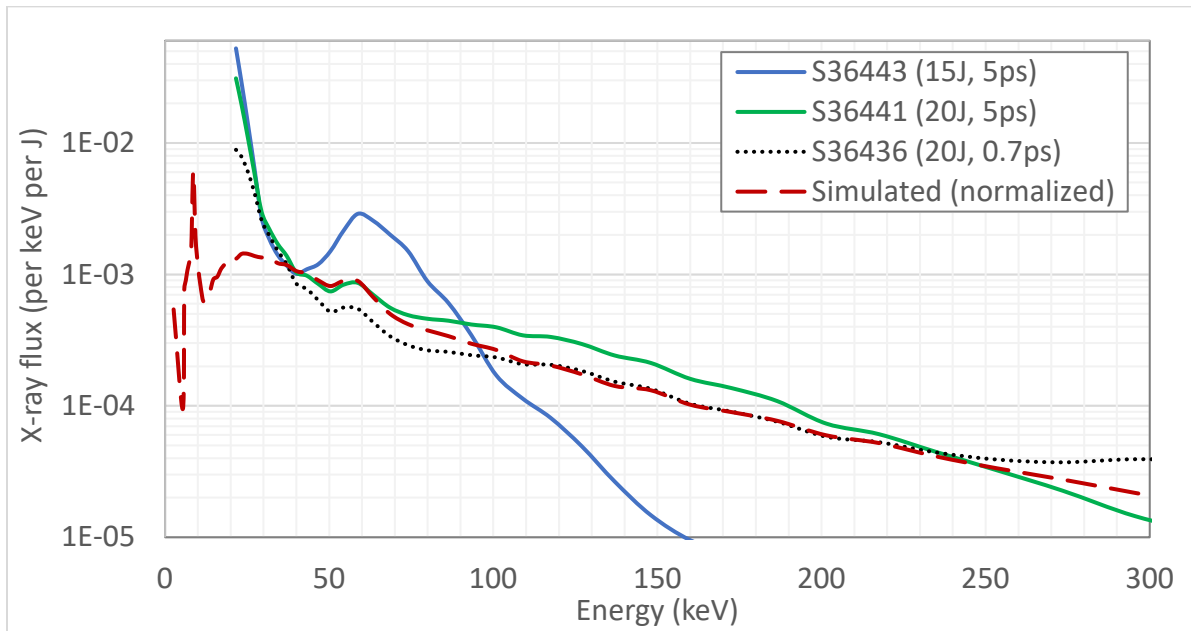


Figure 1. X-ray spectrum from x-ray only shots and corresponding simulation results using PIC and MCNP 6.2

During proton acceleration as there is no high Z material for traditional bremsstrahlung interactions to occur. It is believed that x-rays production occurs mainly due to the circulation of relativistic electrons within the laser-induced plasma. This was found to produce significant background on the image plate stack being used for transmission x-ray radiography, which is oriented nearly orthogonal to the proton source. The x-ray spectra in Figure 2 are shown for the proton-only shots and are normalized per Joule of the Backlighter laser energy driving the proton beam. When laser energy increases the shape of the x-ray spectrum is relatively constant, but photon production increases significantly. Shielding the image plate stack from the x-rays produced during proton production will be essential for enabling simultaneous dual-axis proton and x-ray radiography.

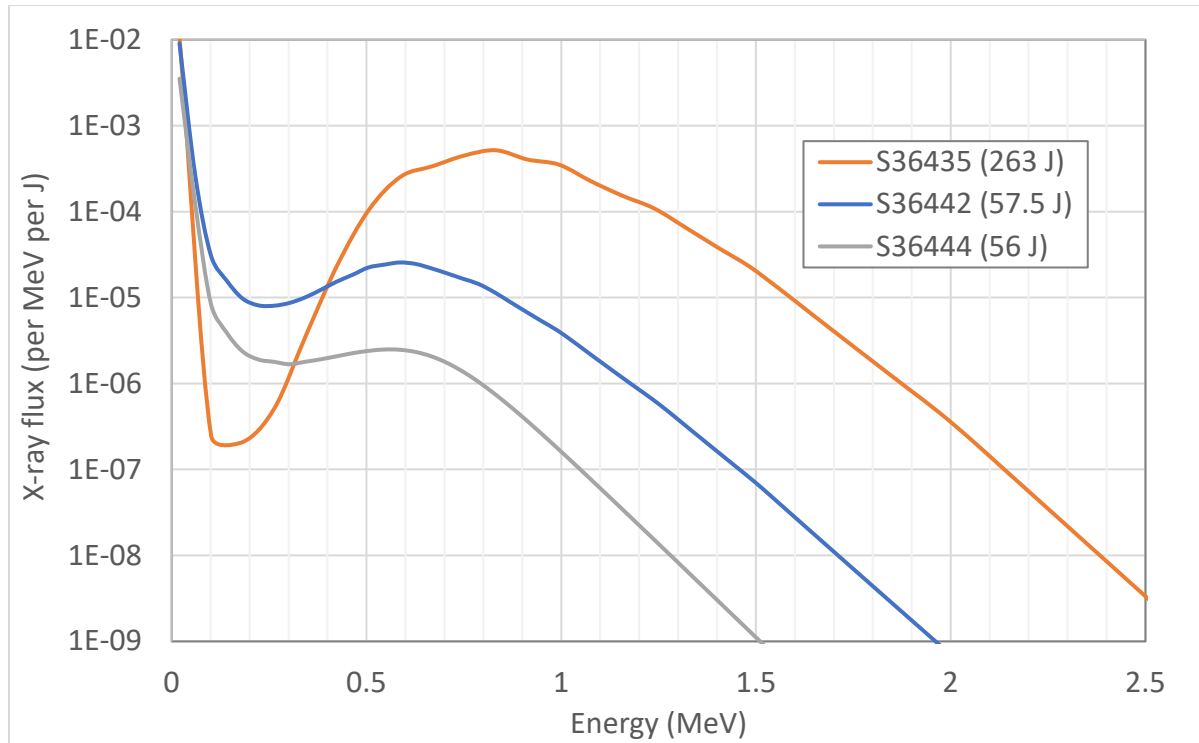
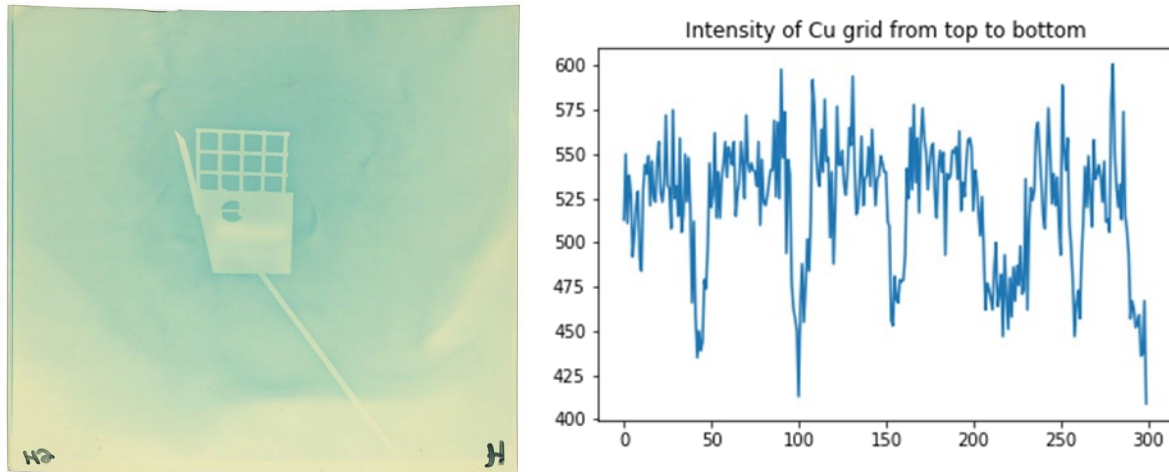


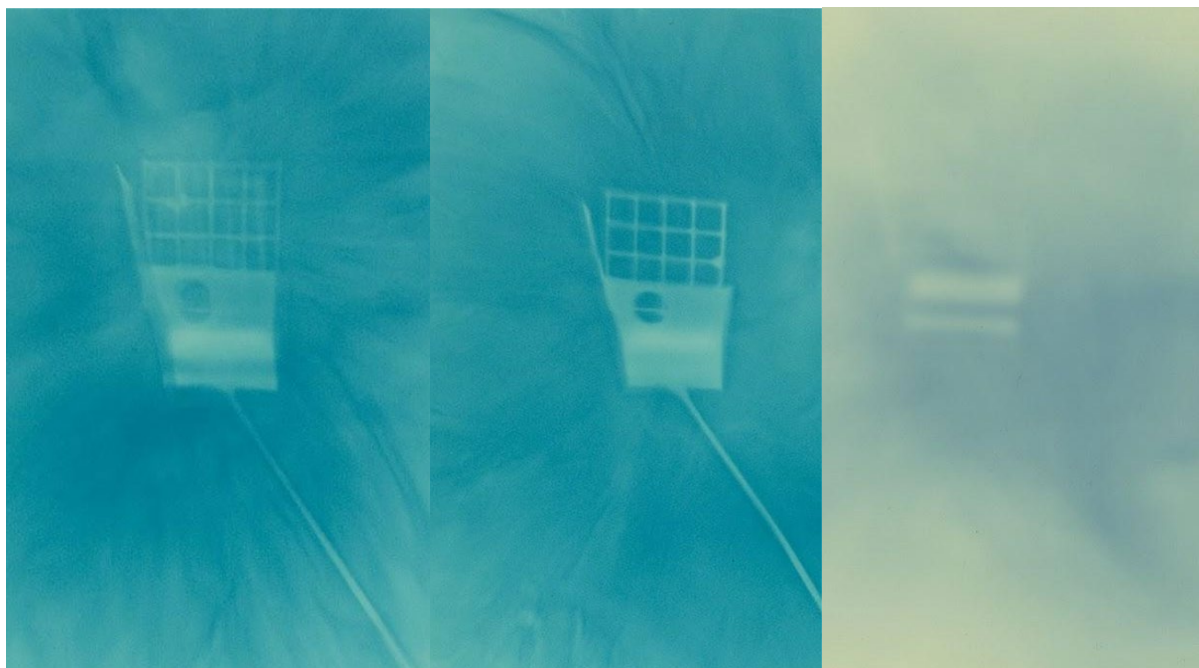
Figure 2. X-ray spectrum measured during the proton only shots

Proton radiography

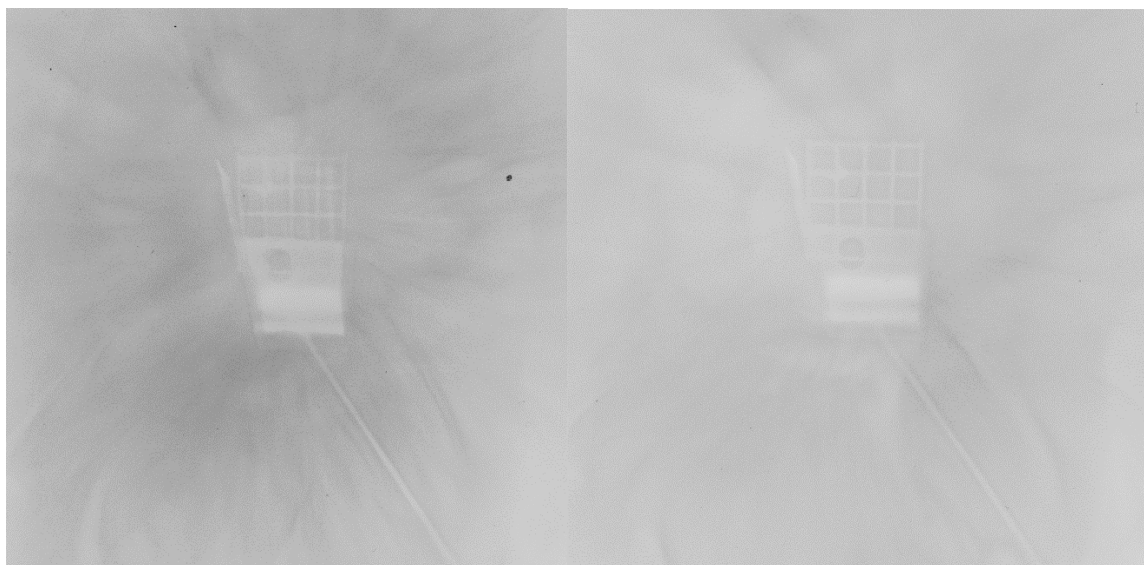
The sharpest proton radiograph of the day was obtained with 60 J (36442 #2).



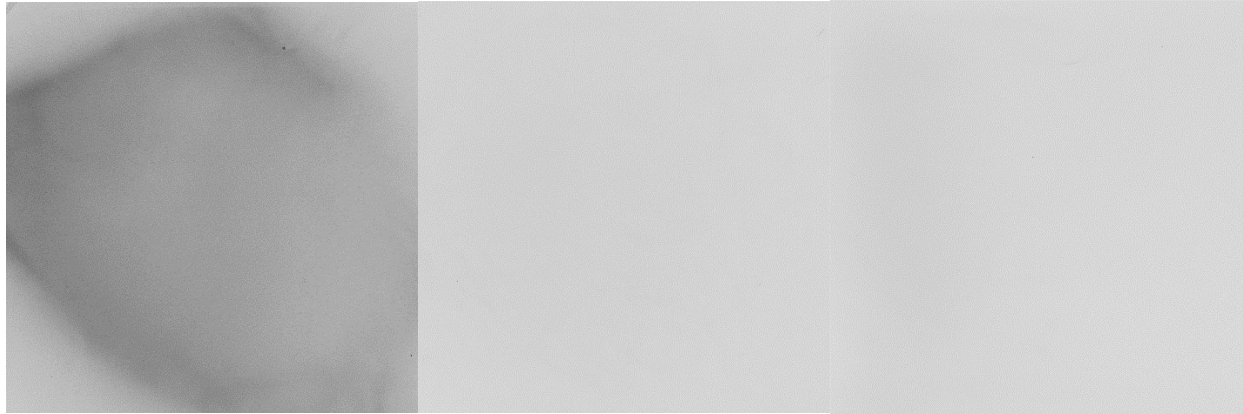
Various qualitative issues were observed in the proton radiographs, including duplicated static object images (below left 36435 #2), curved stalks indicating warped images (below center 36439 #2), and substantial background radiation (below right 36435 #11), particularly in the M-films at the back of the RCF stacks. We believe that the observed background radiation is due to high energy electrons; however, this has not been directly confirmed.



When ghosting was observed, it was stronger on the films located early in the RCF stack as compared to those located deeper into the RCF stack. This can be seen in the following two images for shot 36437 (proton only, 492.4 J), where film #3 on the left had noticeably stronger ghosting than film #4 on the right.



Structure in flat field images (no radiography of a static object) was noted, particularly on early films in the RCF stack corresponding to low energy (~ 4 -13 MeV) protons. Below are flat field images from shot 36444 (proton only, 56 J), where substantial structure can be seen in film #1 on the left, while significantly less structure can be seen in films #2 (>13.1 MeV) and #3 (>18.9 MeV) in the center and on the right, respectively.

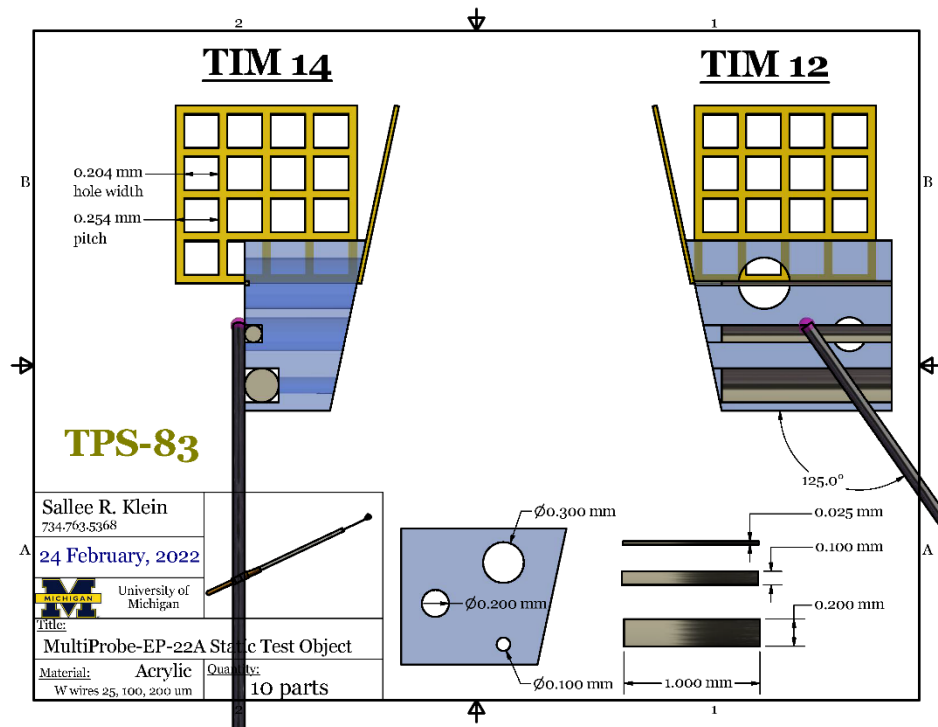


Acknowledgements

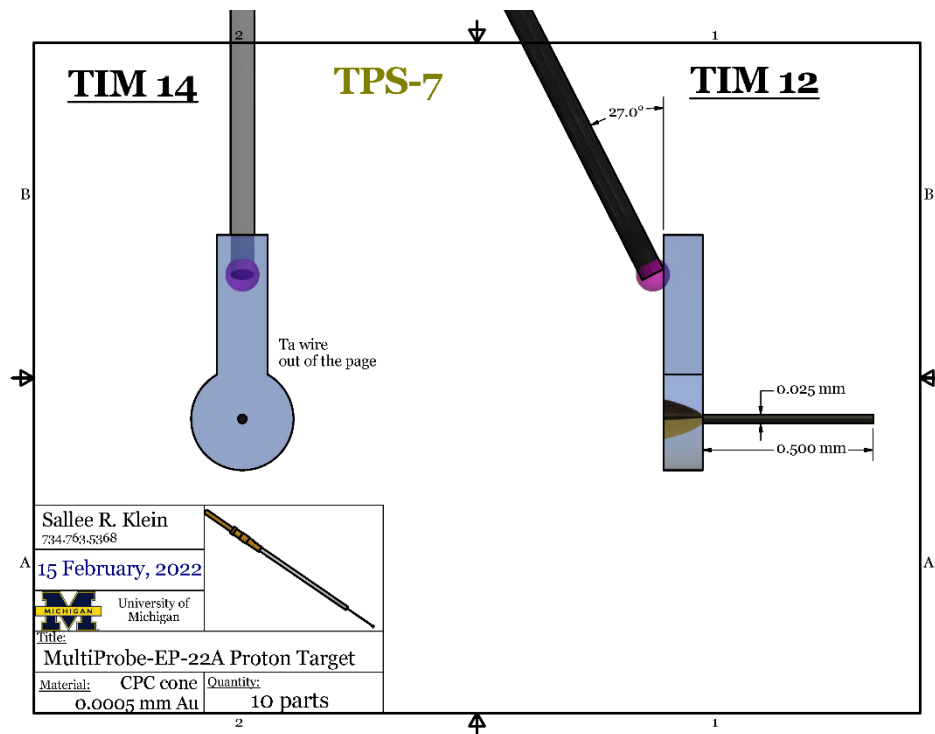
This work was supported by the U.S. Department of Energy through the Los Alamos National Laboratory (LANL). LANL is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. DOE (Contract No. 89233218CNA000001). This work was initiated under the LANL LDRD 20180732ER program and continued under OES ADP.

Appendices

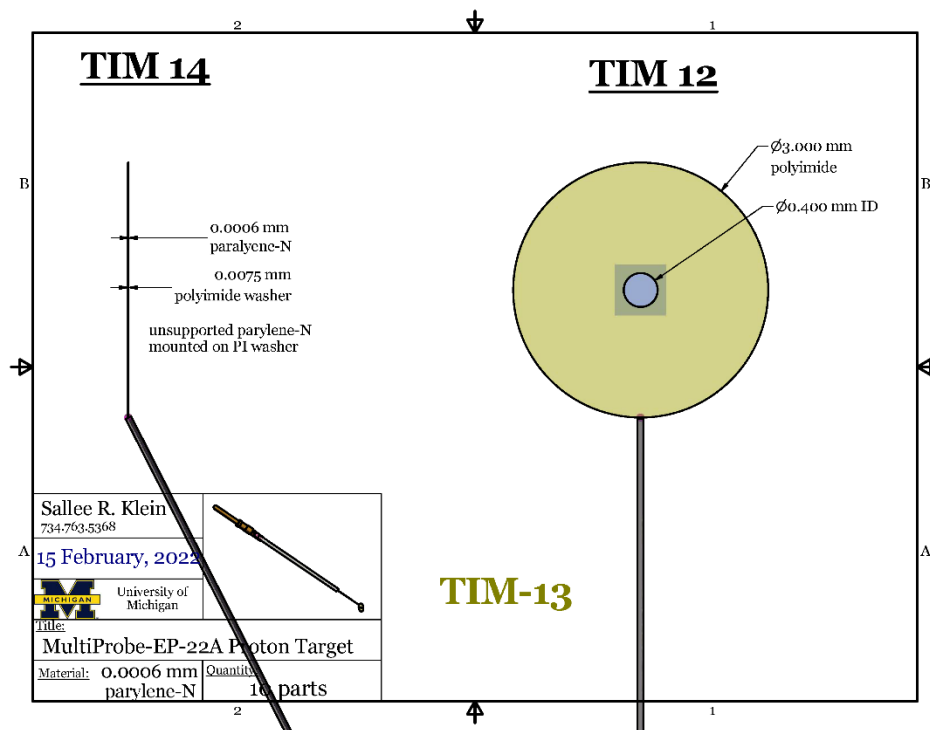
Appendix A: Target Drawing



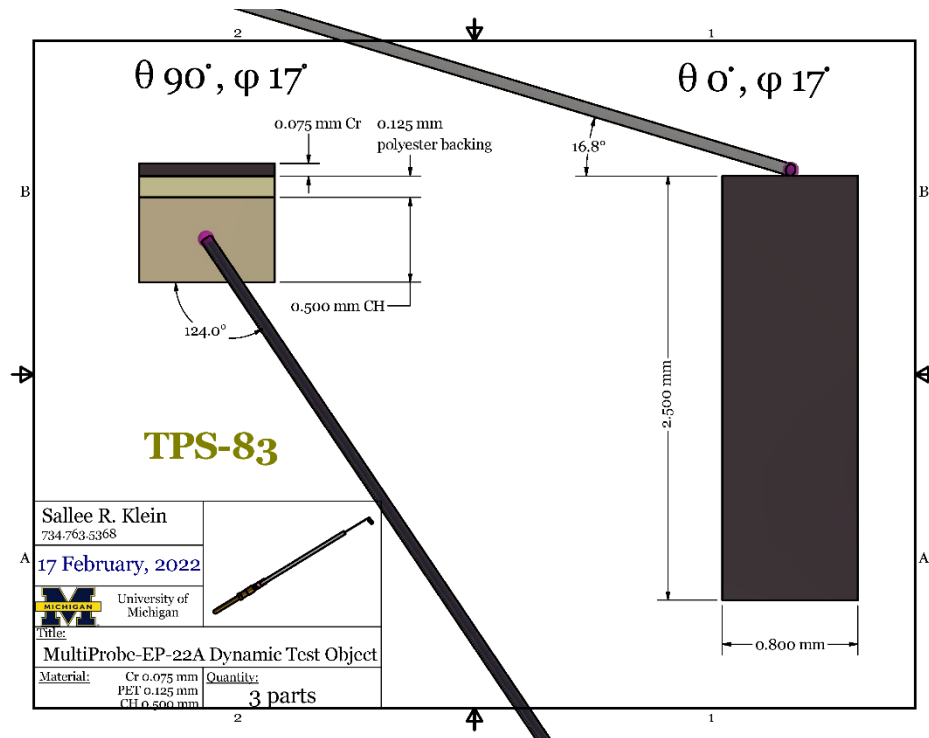
Drawing of the static object.



Drawing of the x-ray target.

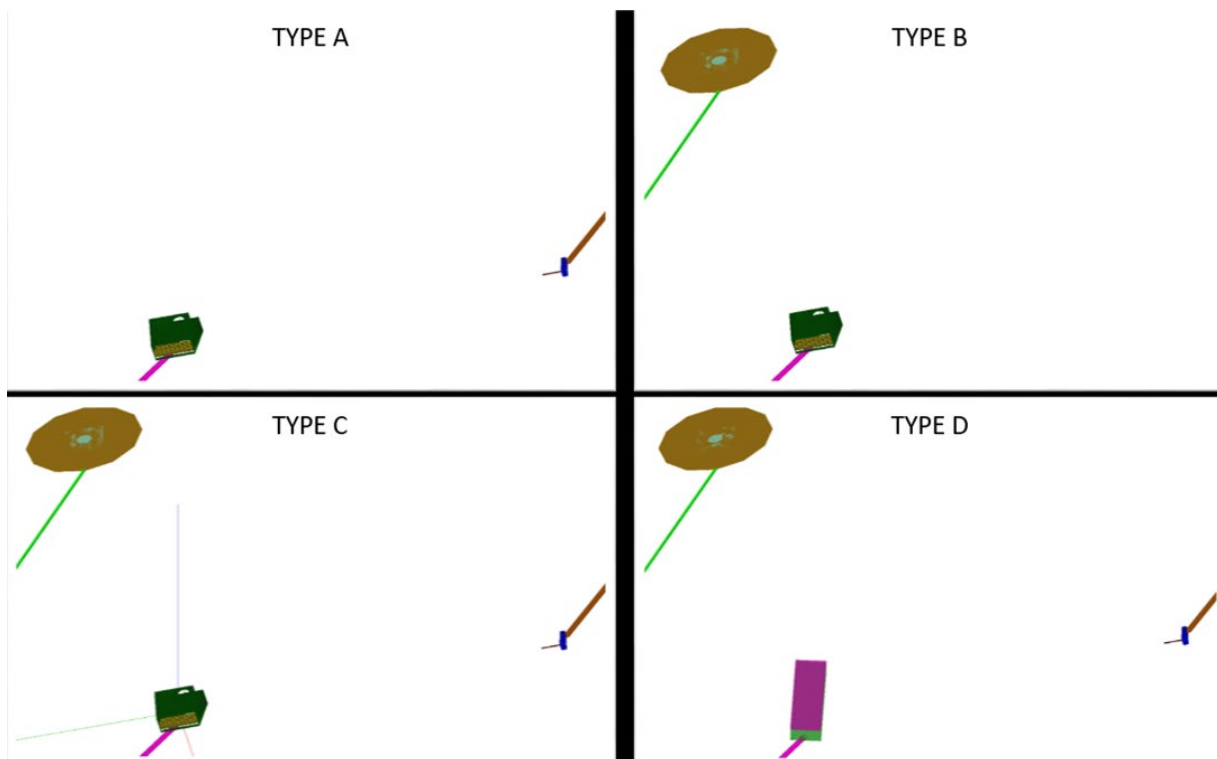


Drawing of the proton target.



Drawing of the dynamic test object that was not fielded on the day.

Appendix B: VisRad layouts



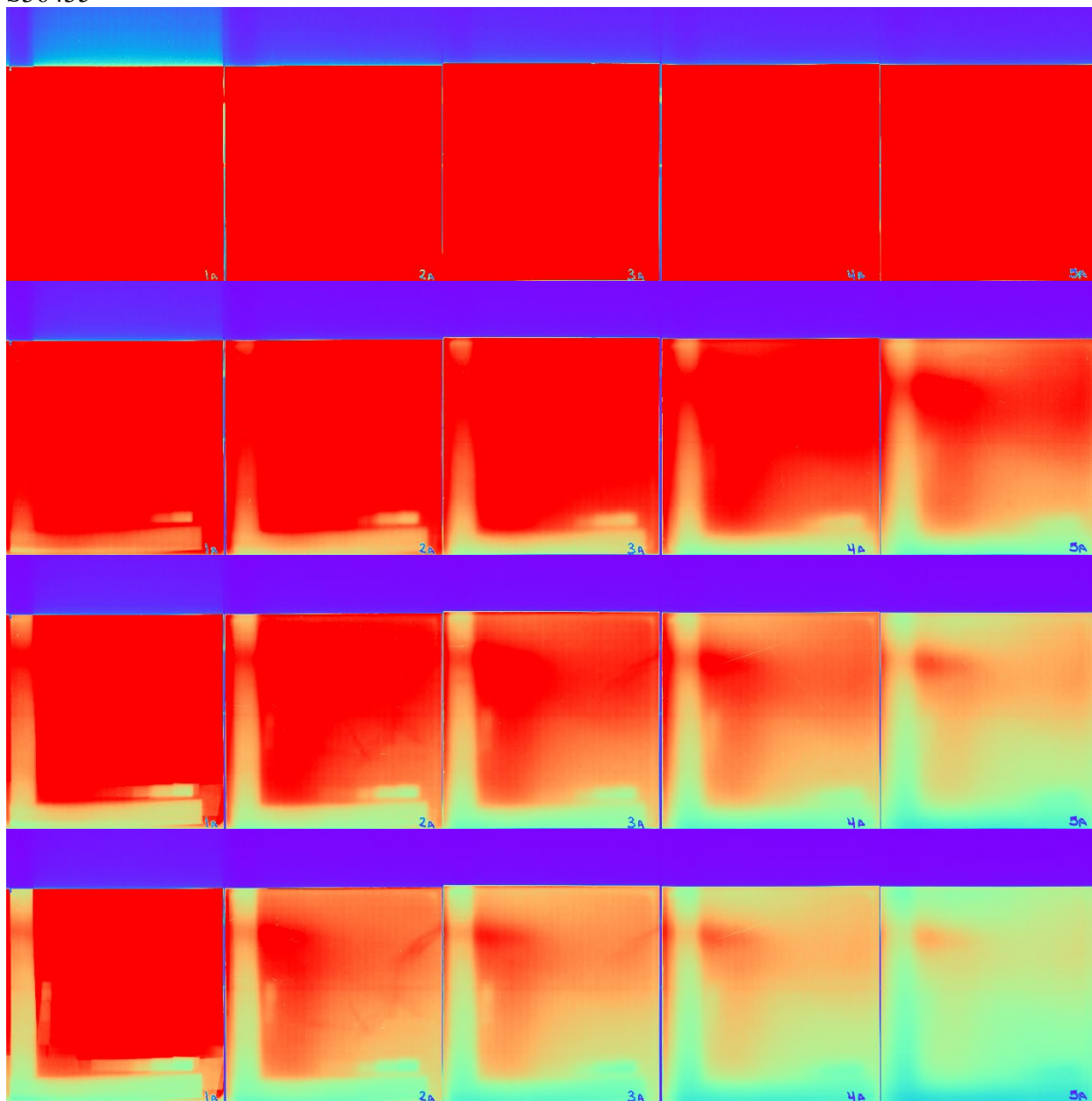
VisRad layouts of the various types of shots planned for the day.

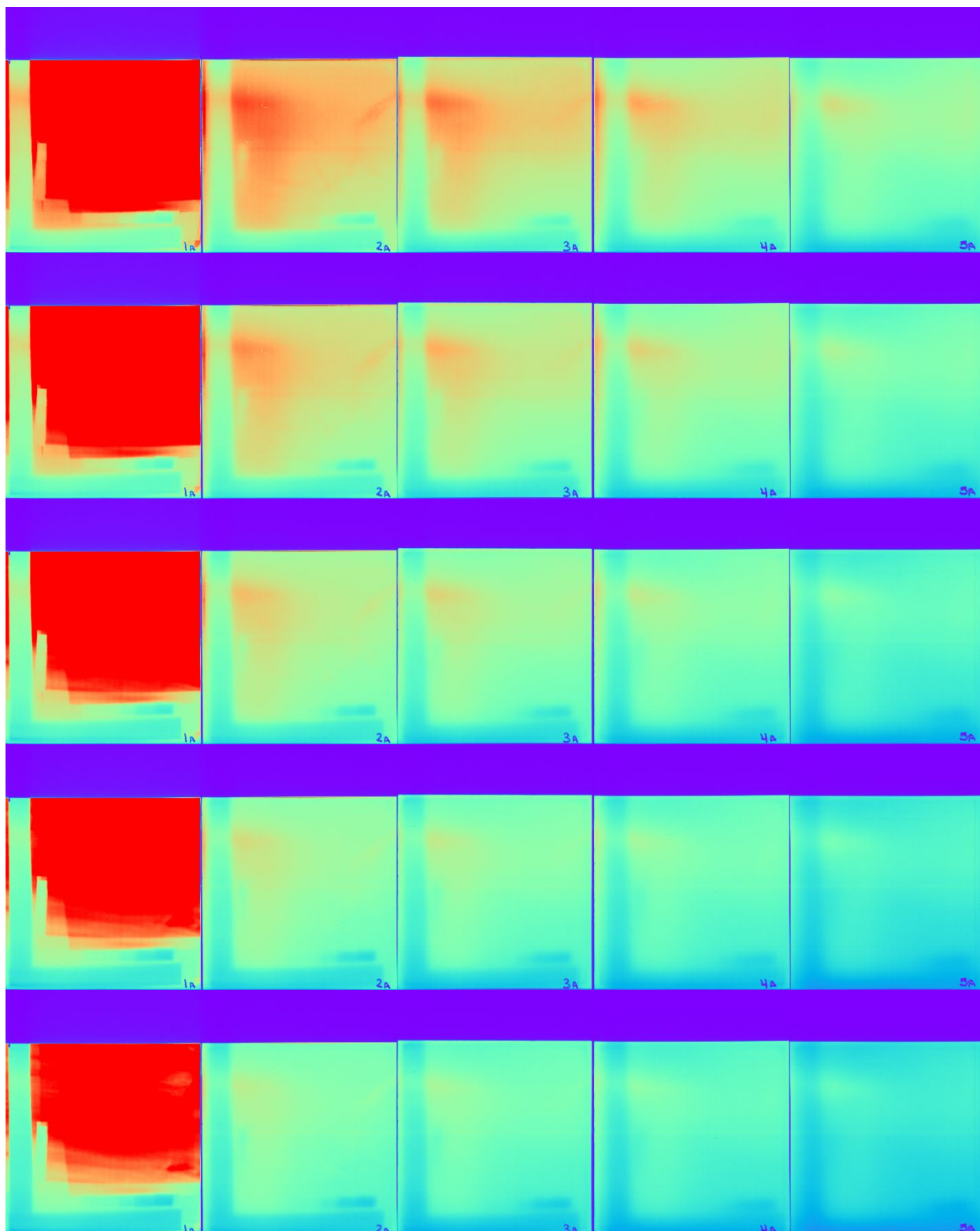
Appendix C: Raw IP and RCF images from the day

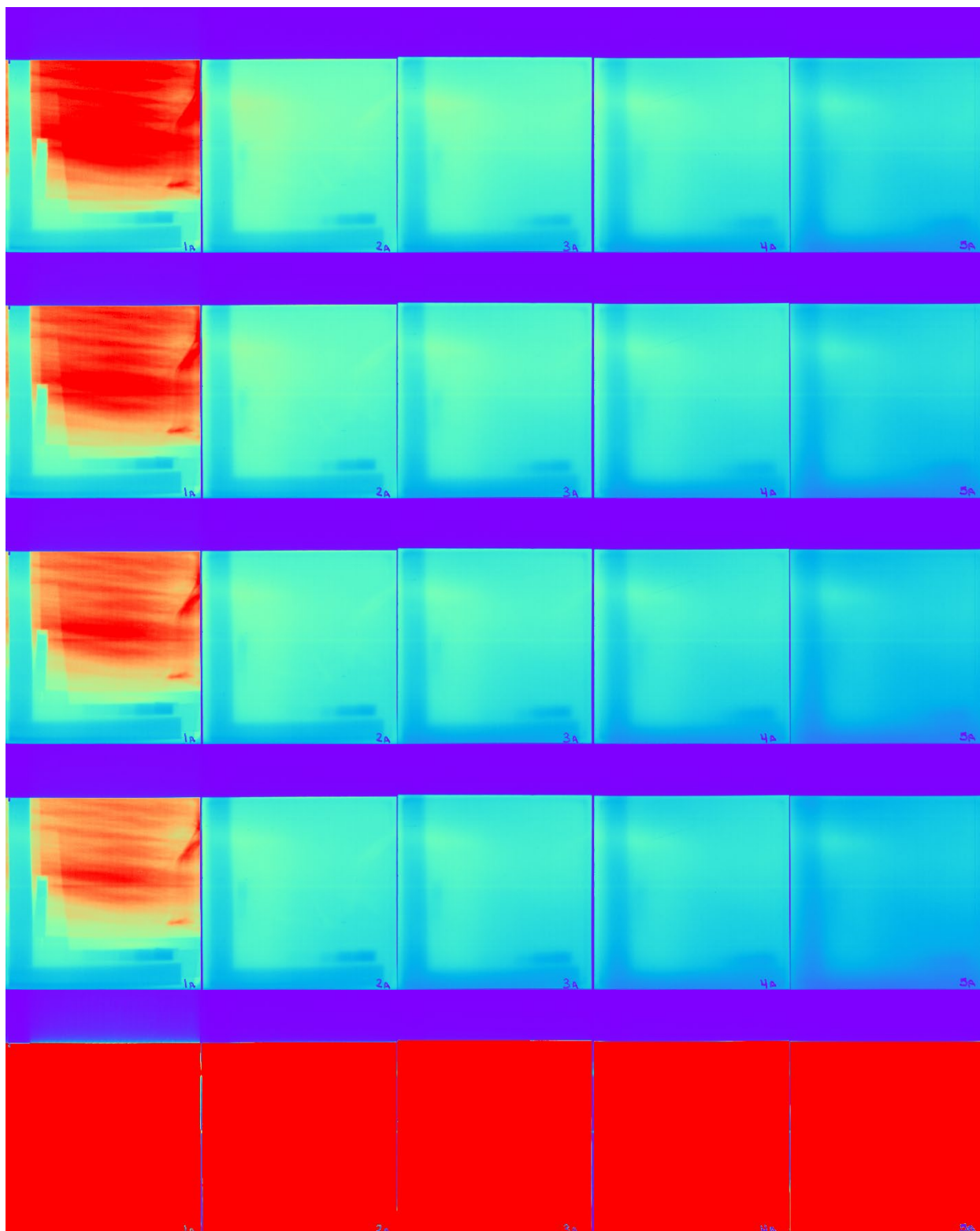
Image plate data

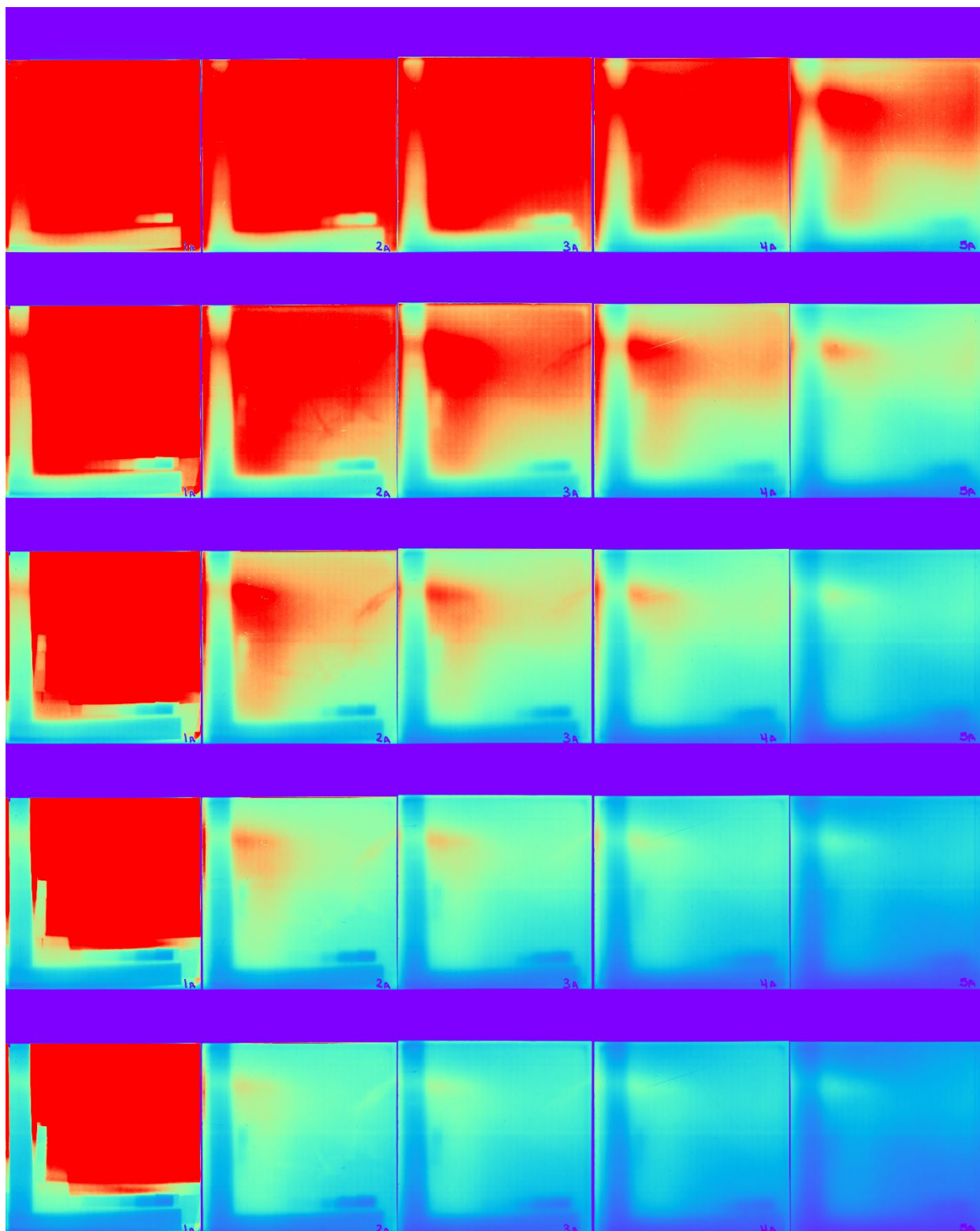
For each shot, the images are for sequential scans of the gel_data_nta, followed by the nta14 data.

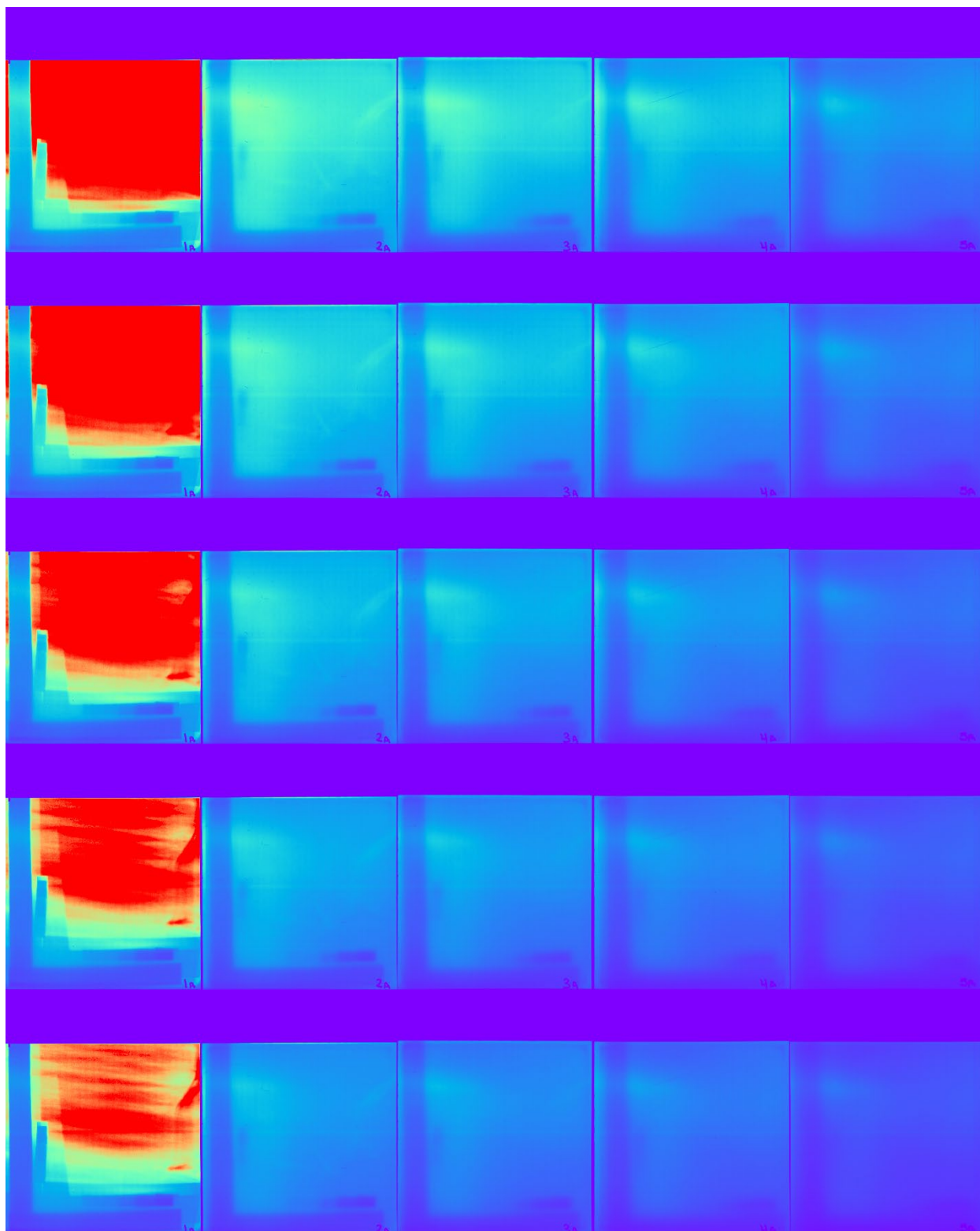
S36435

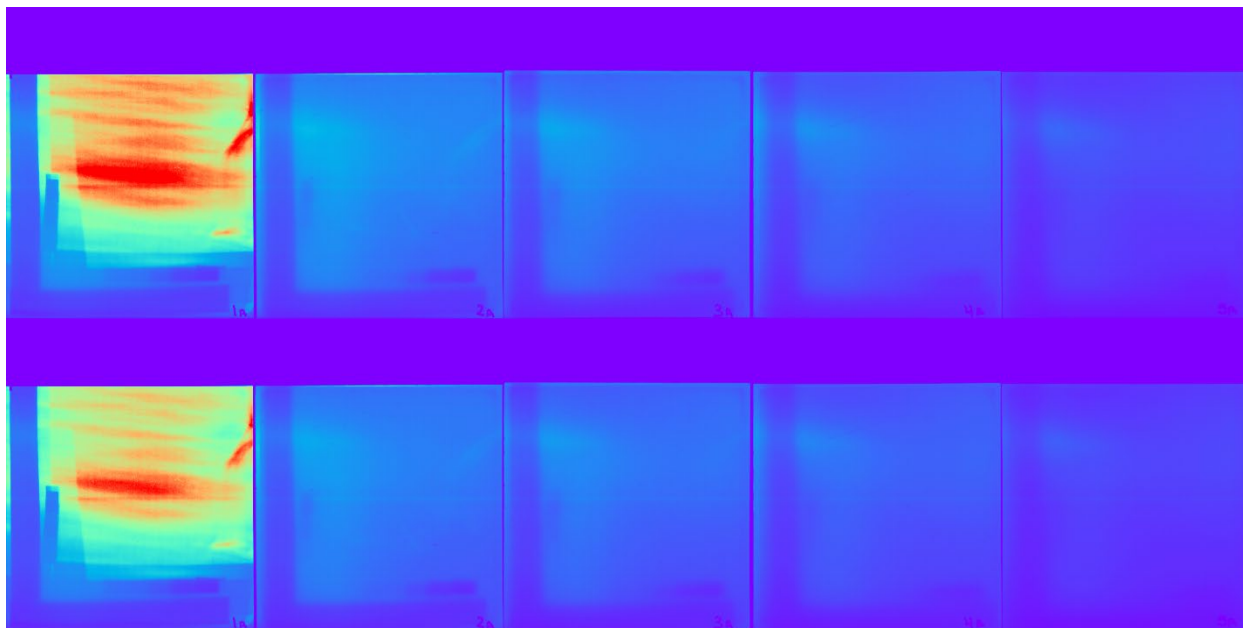




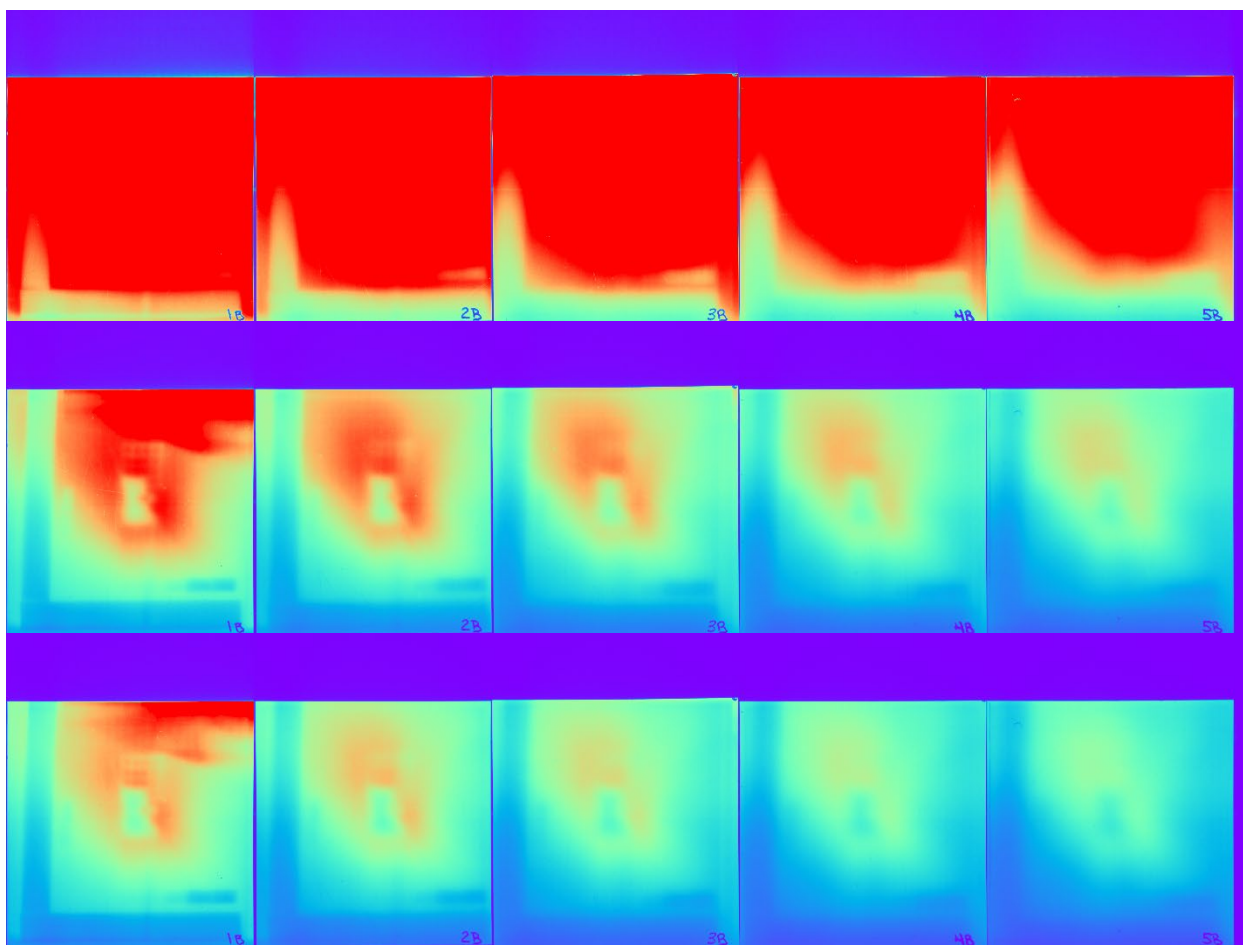


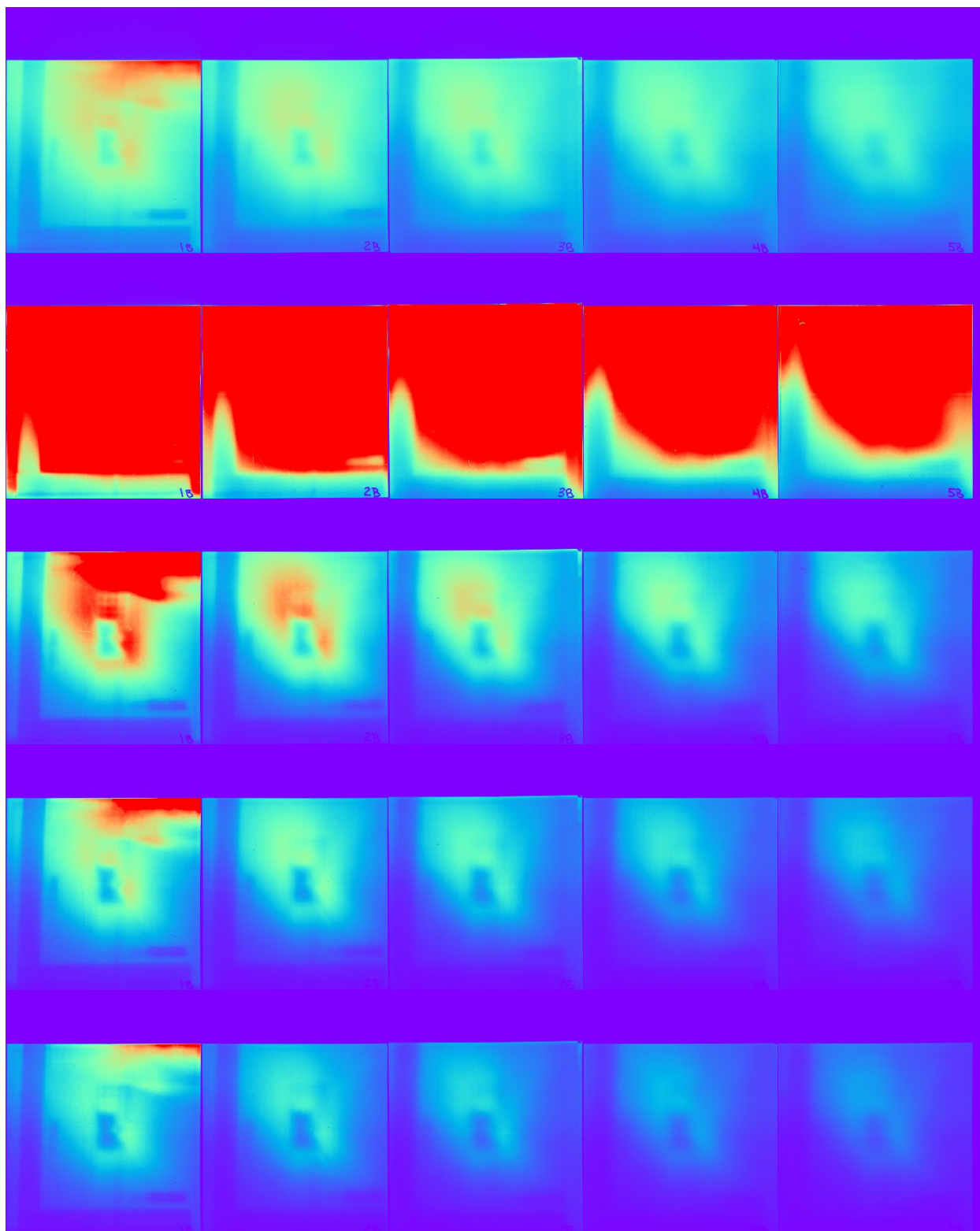




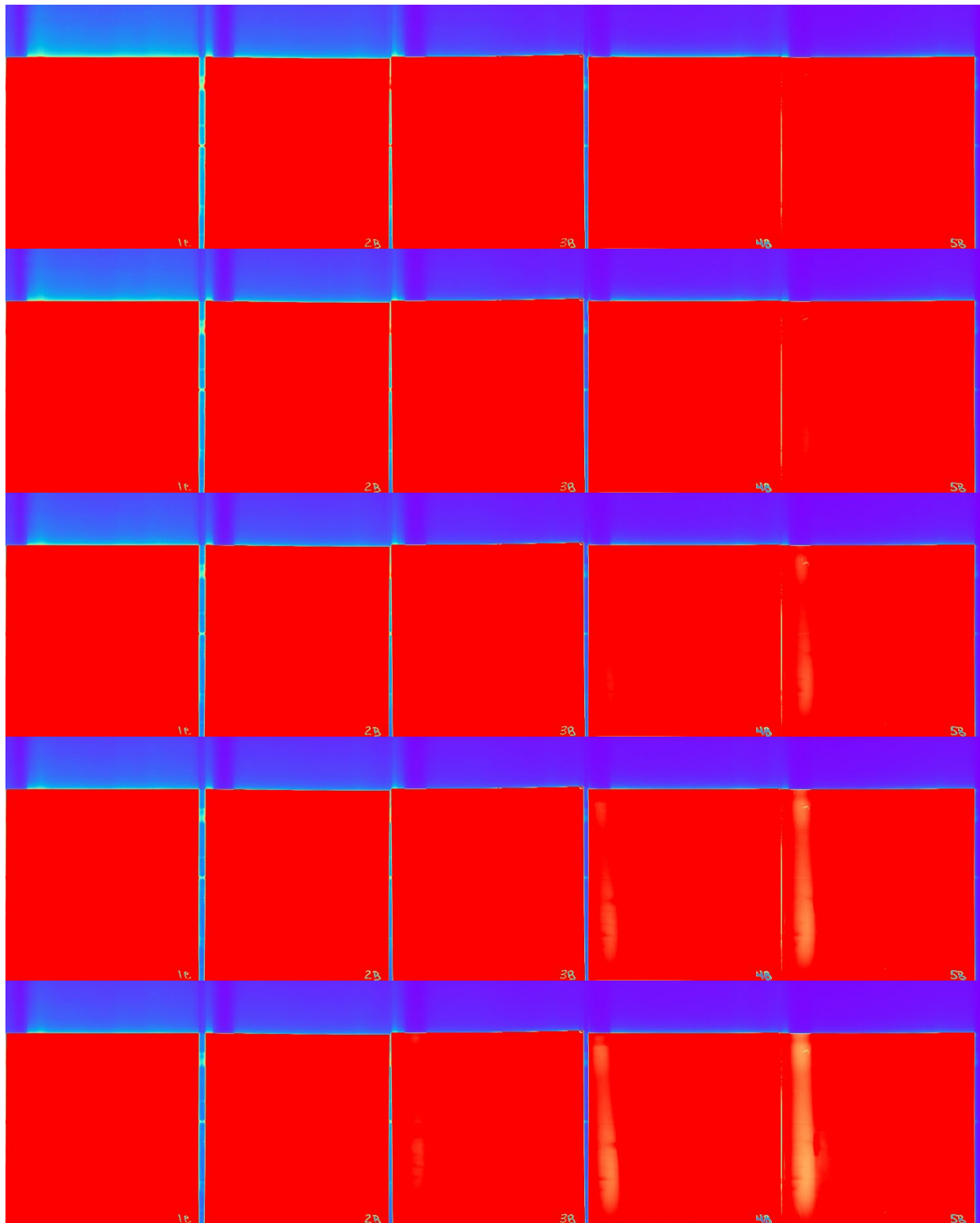


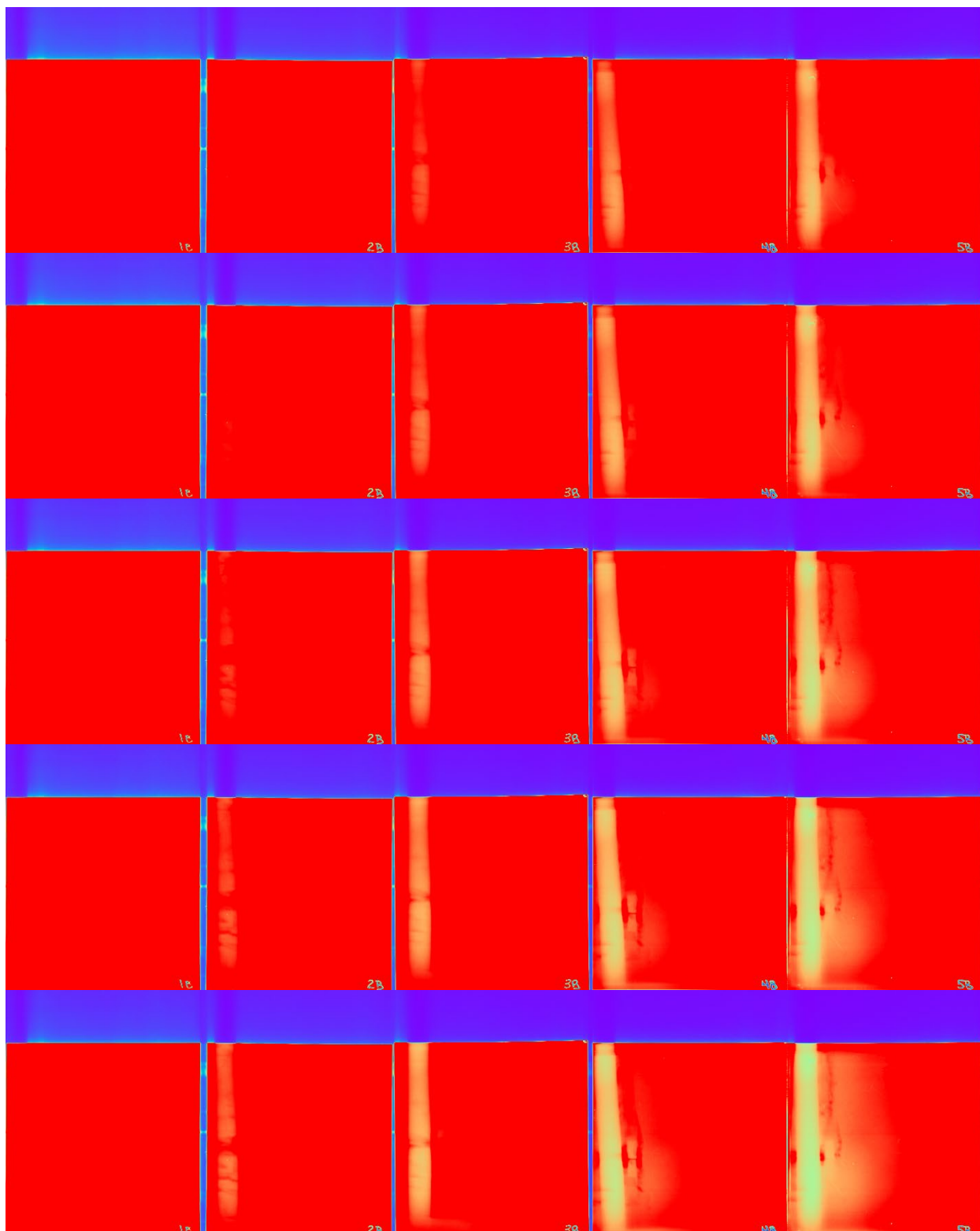
Shot 36436

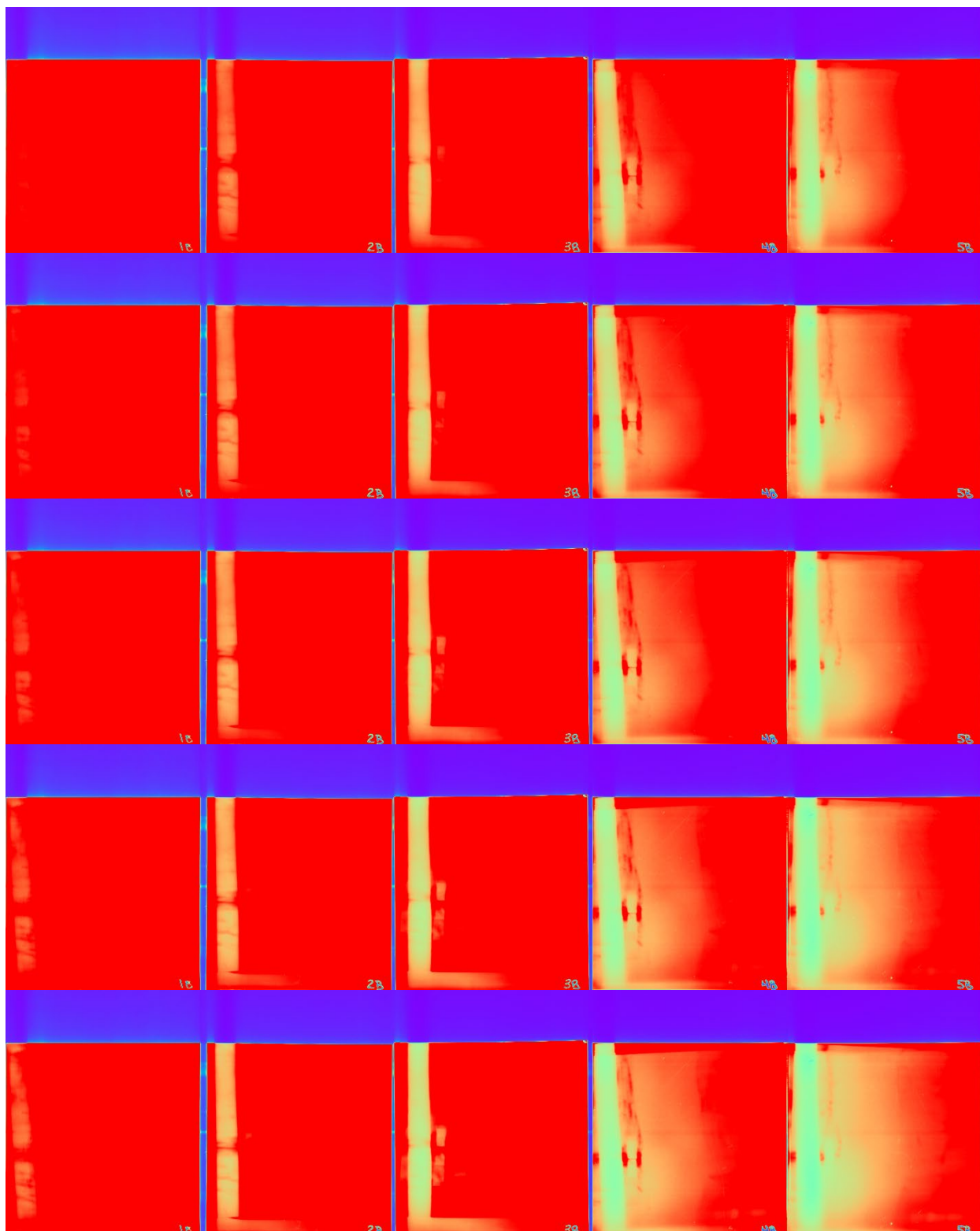


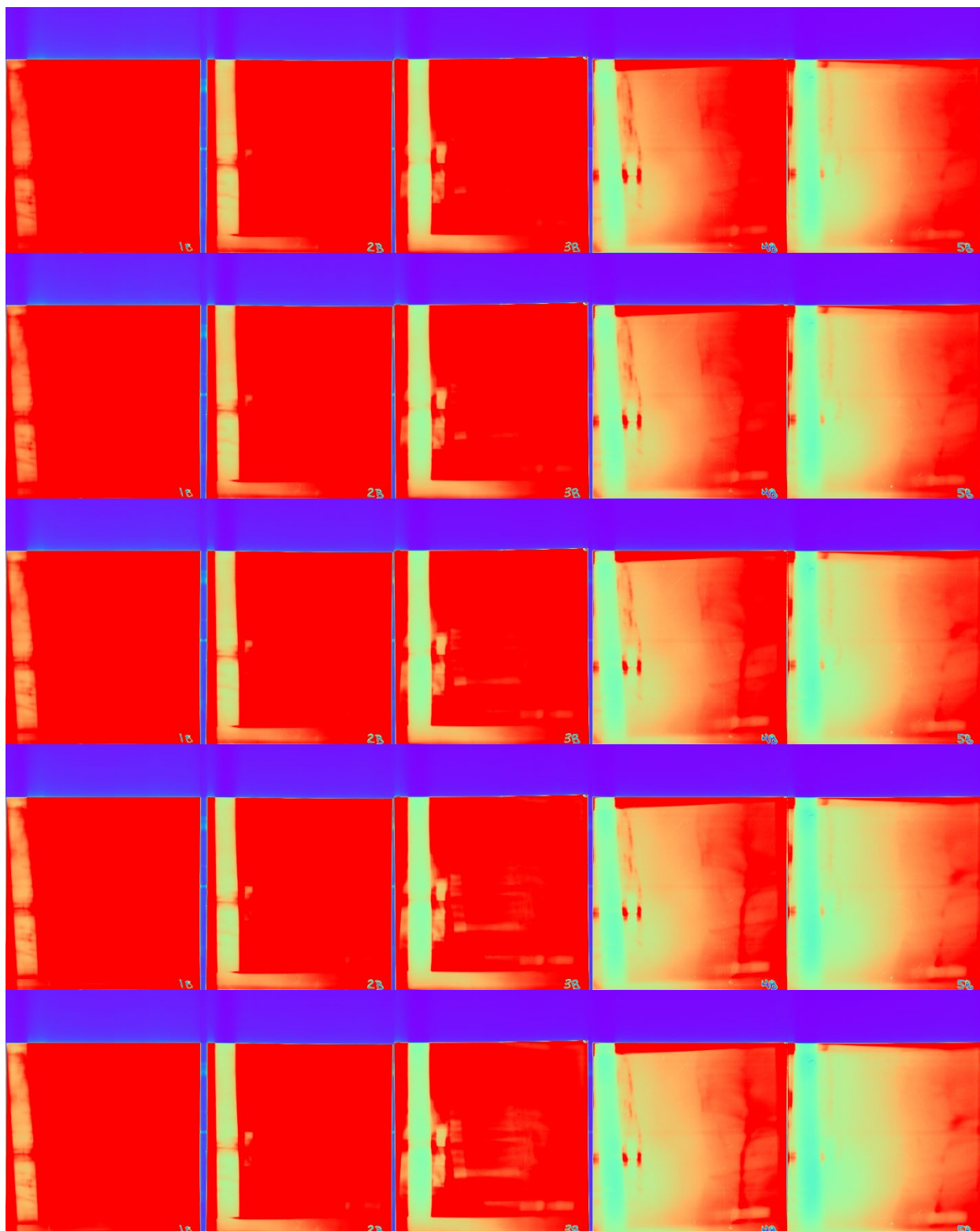


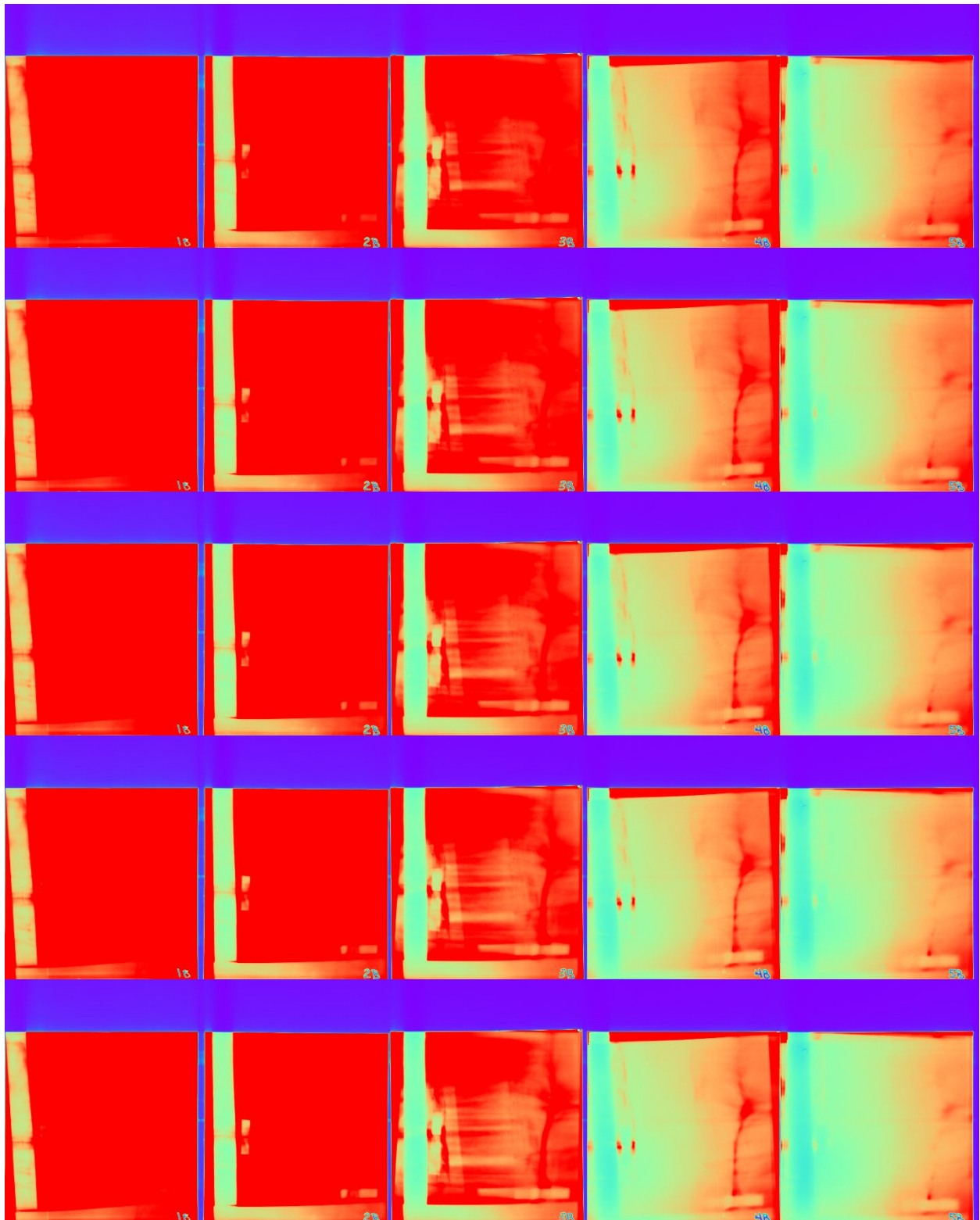
Shot 36438

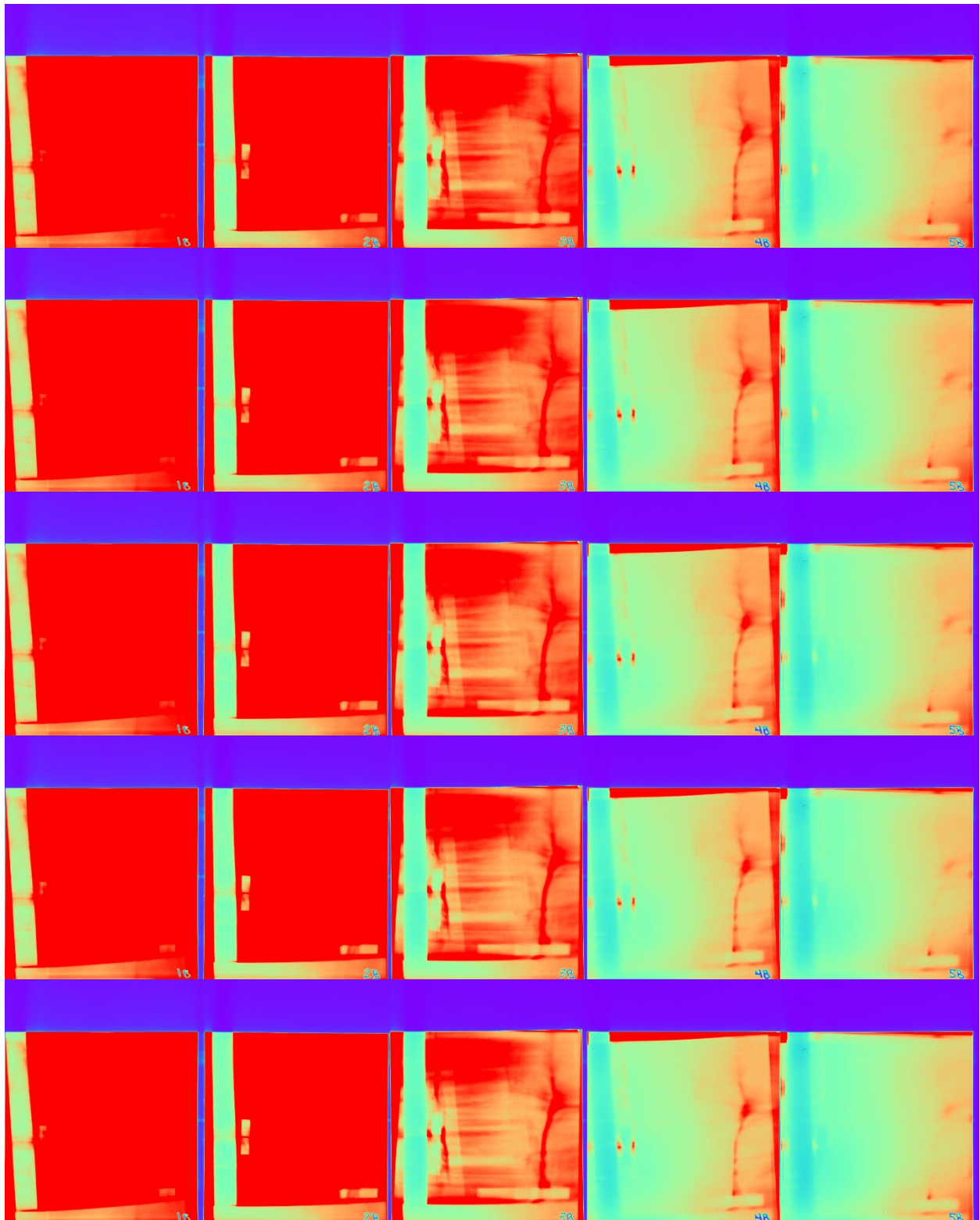


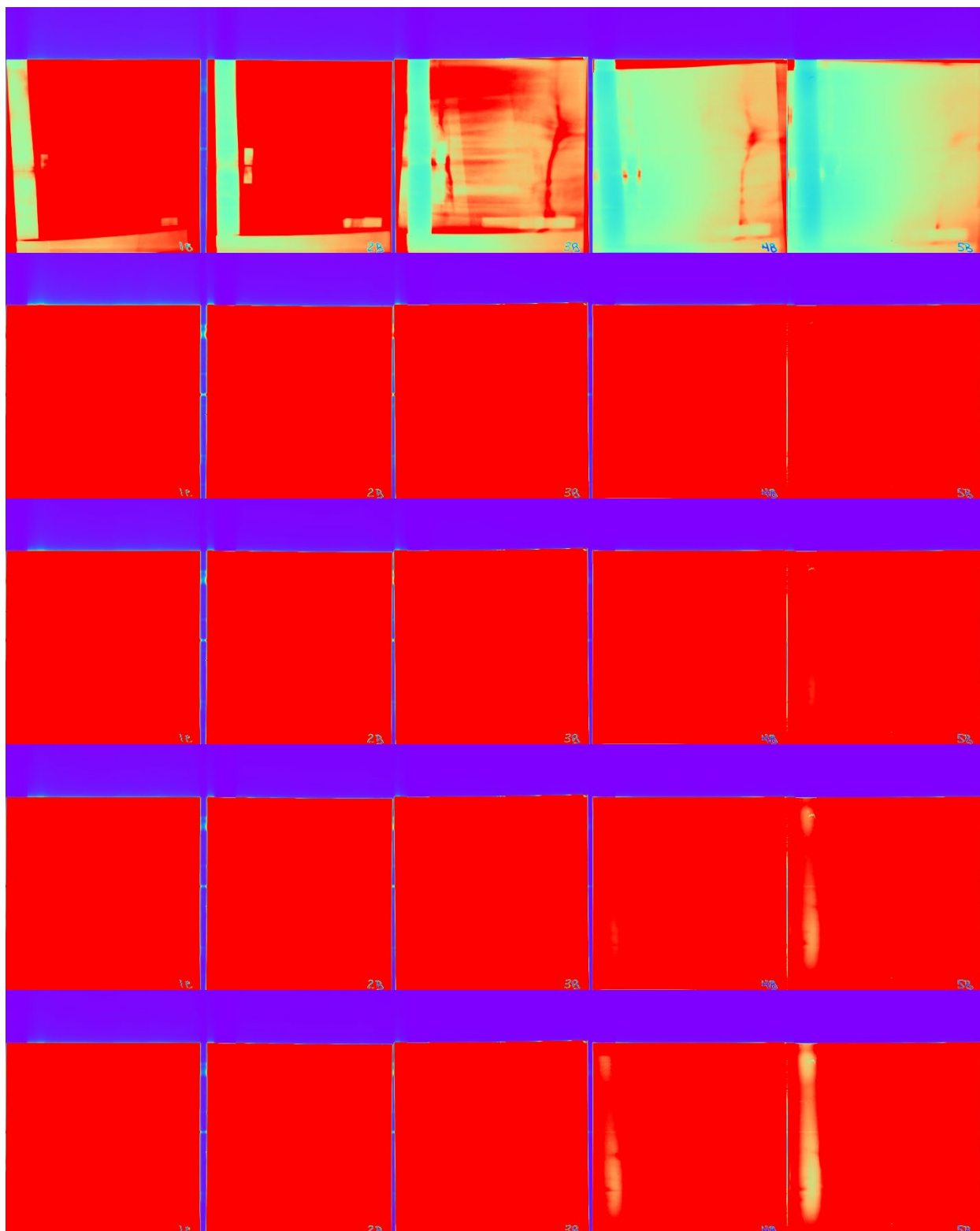


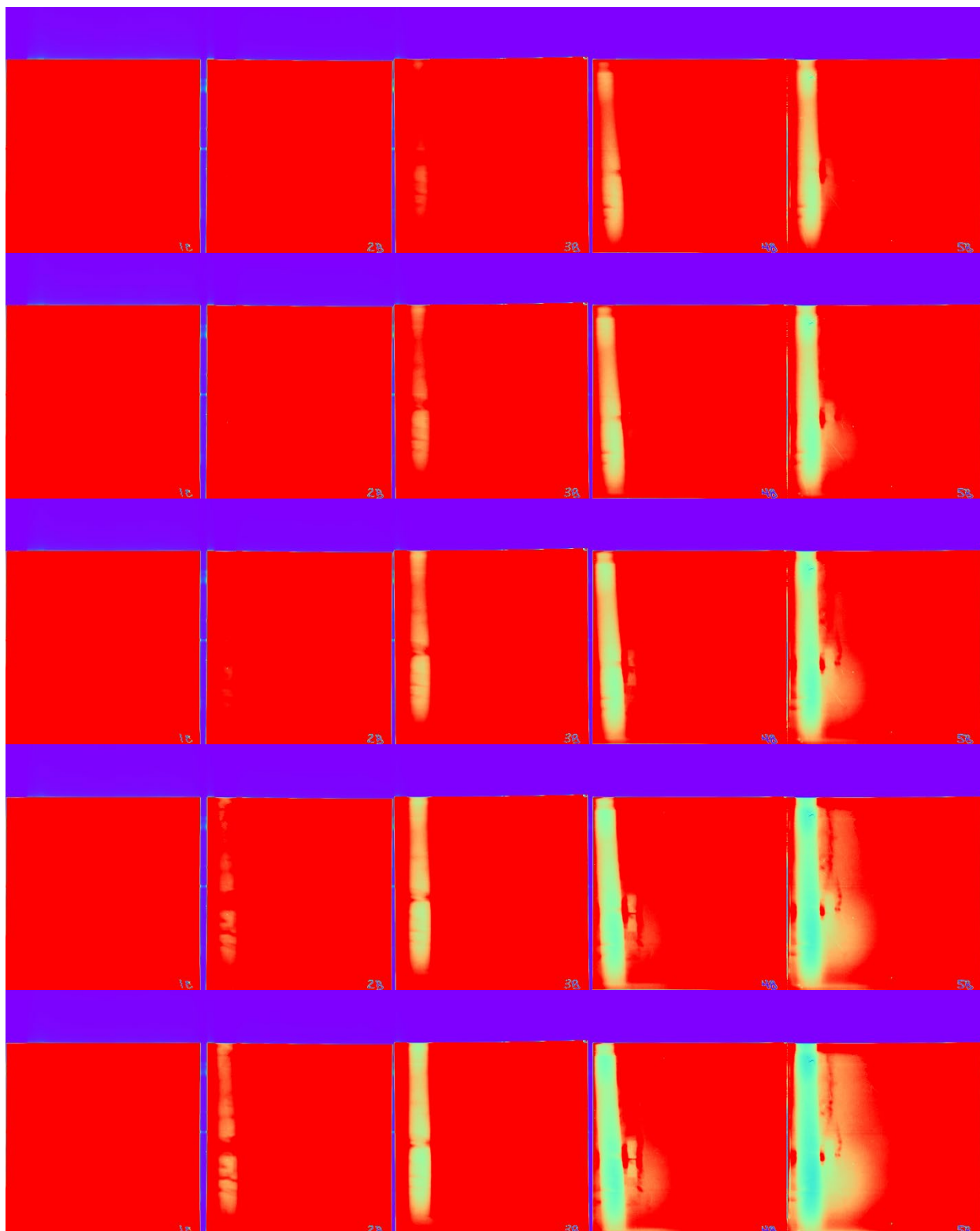


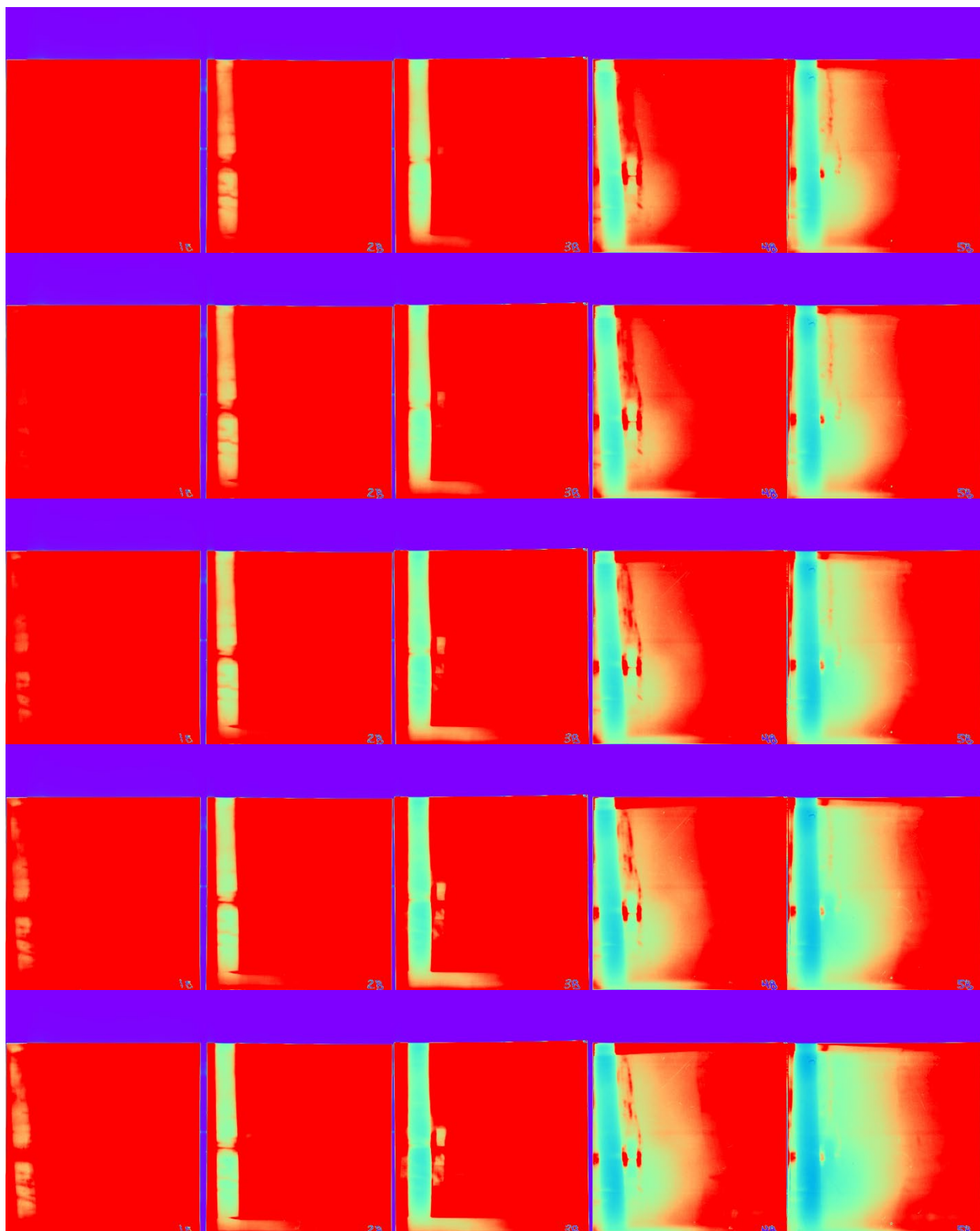


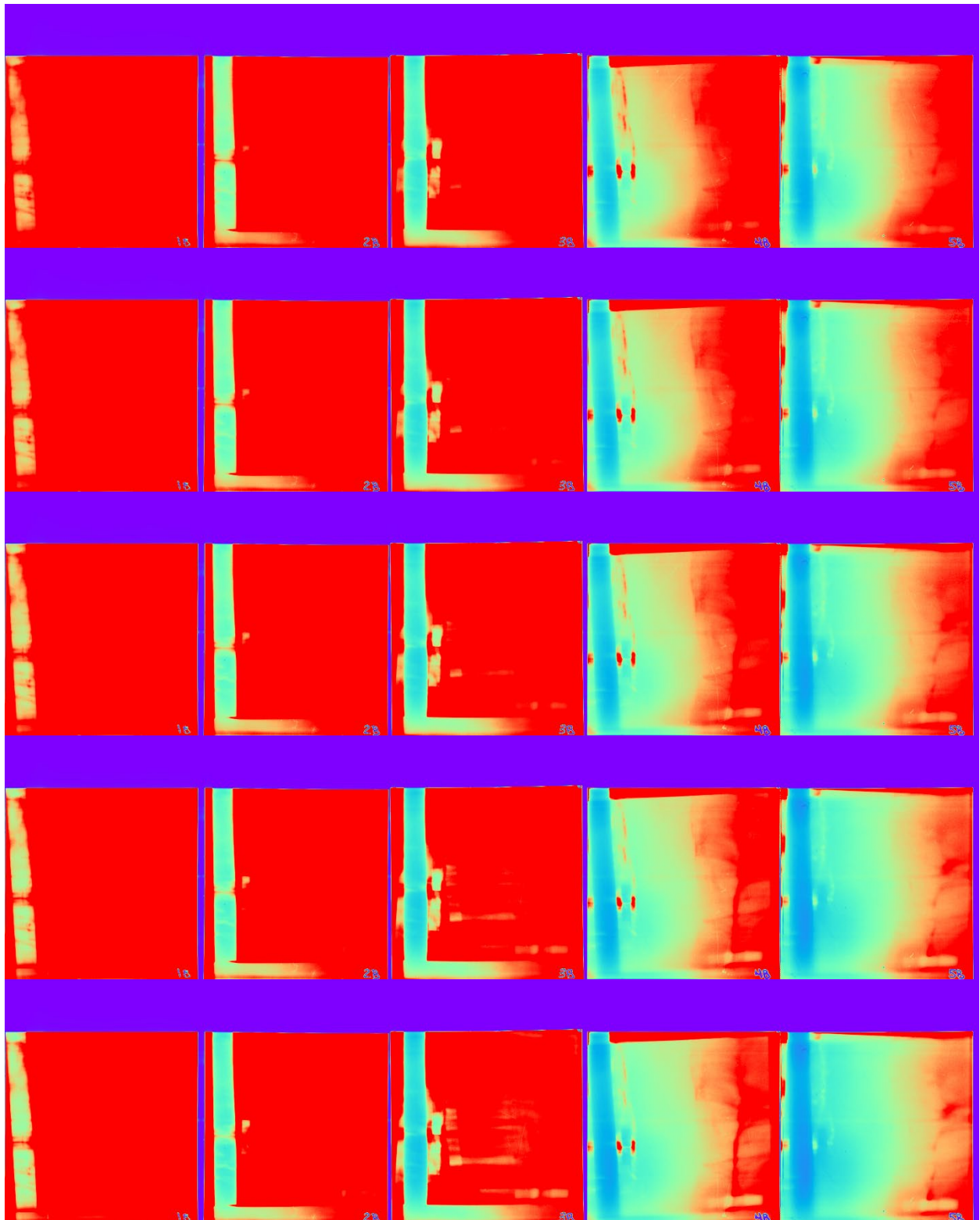


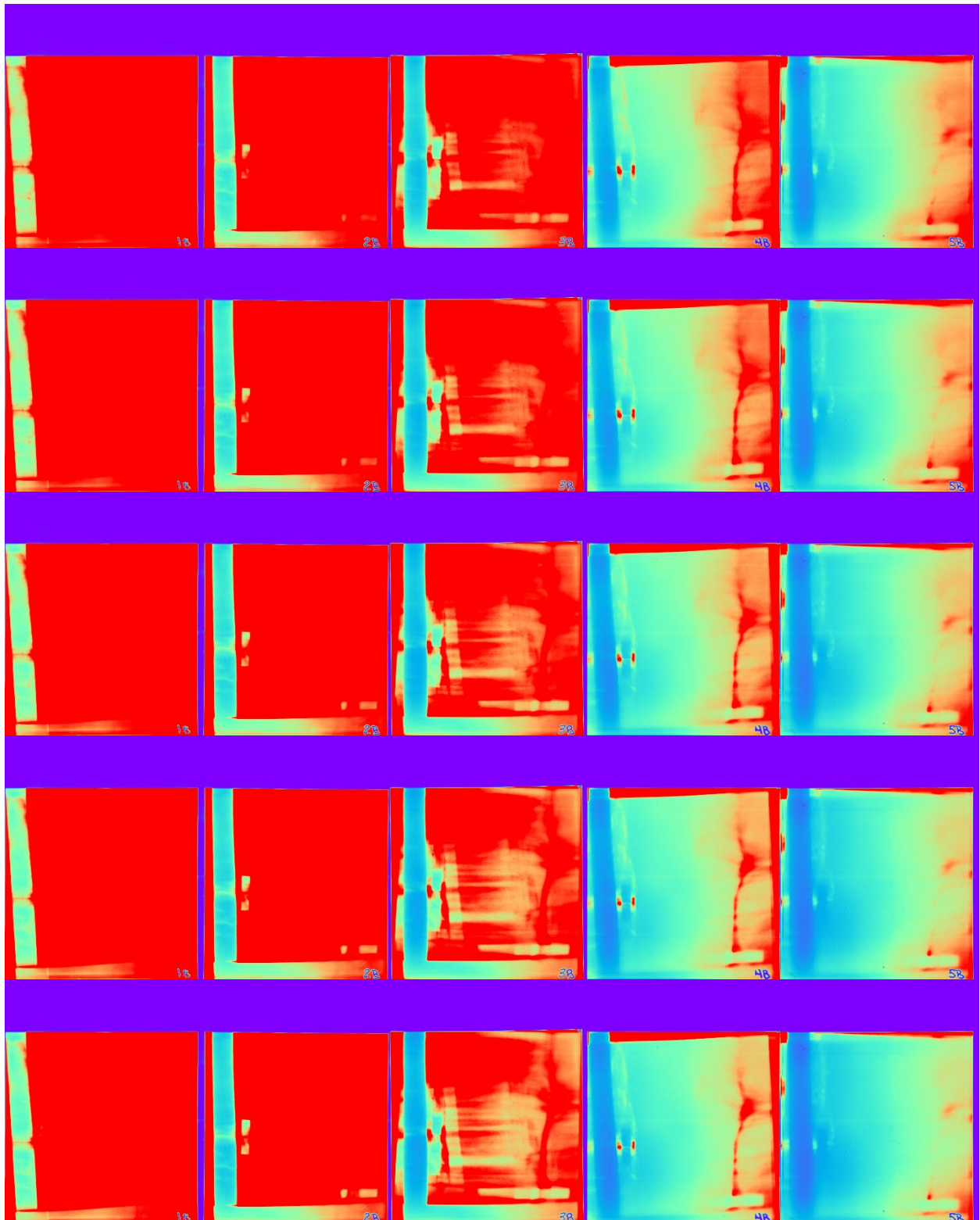


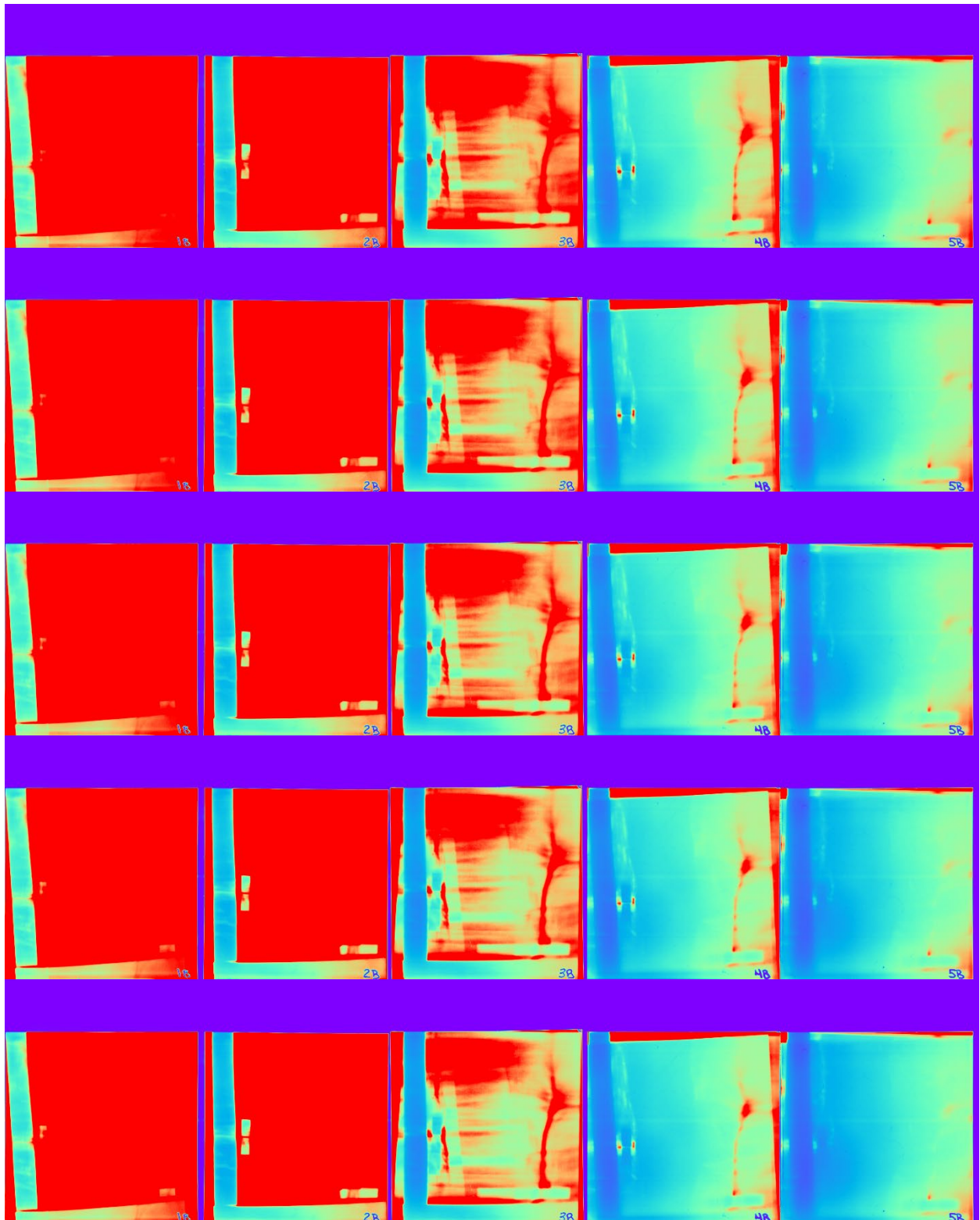


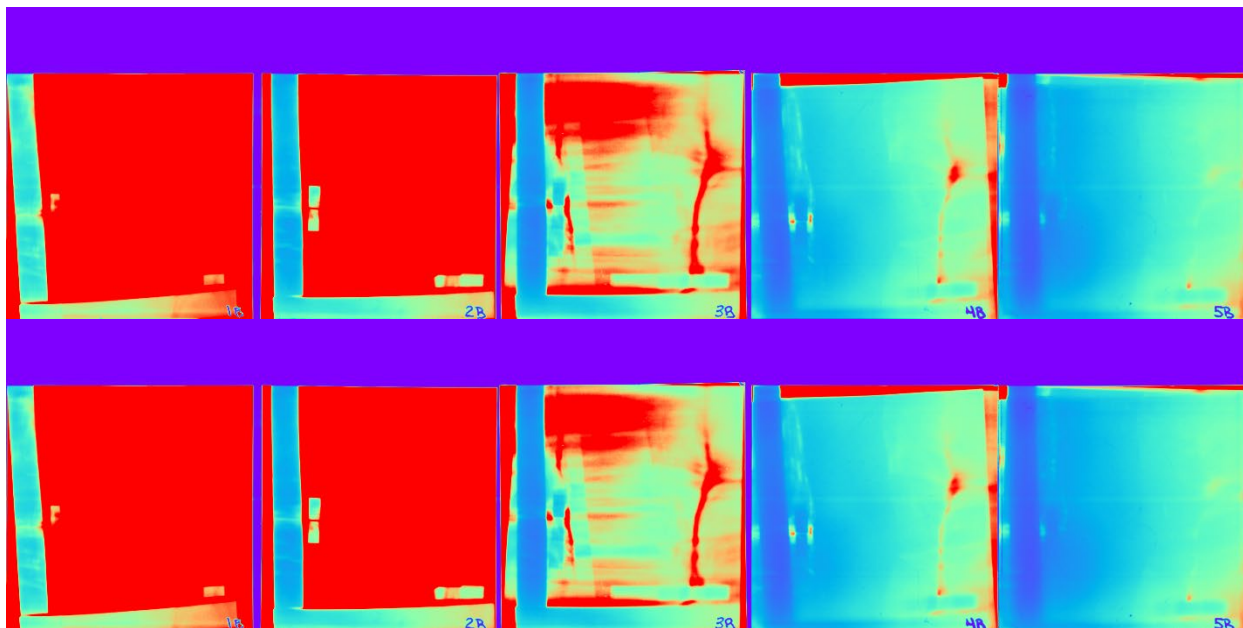




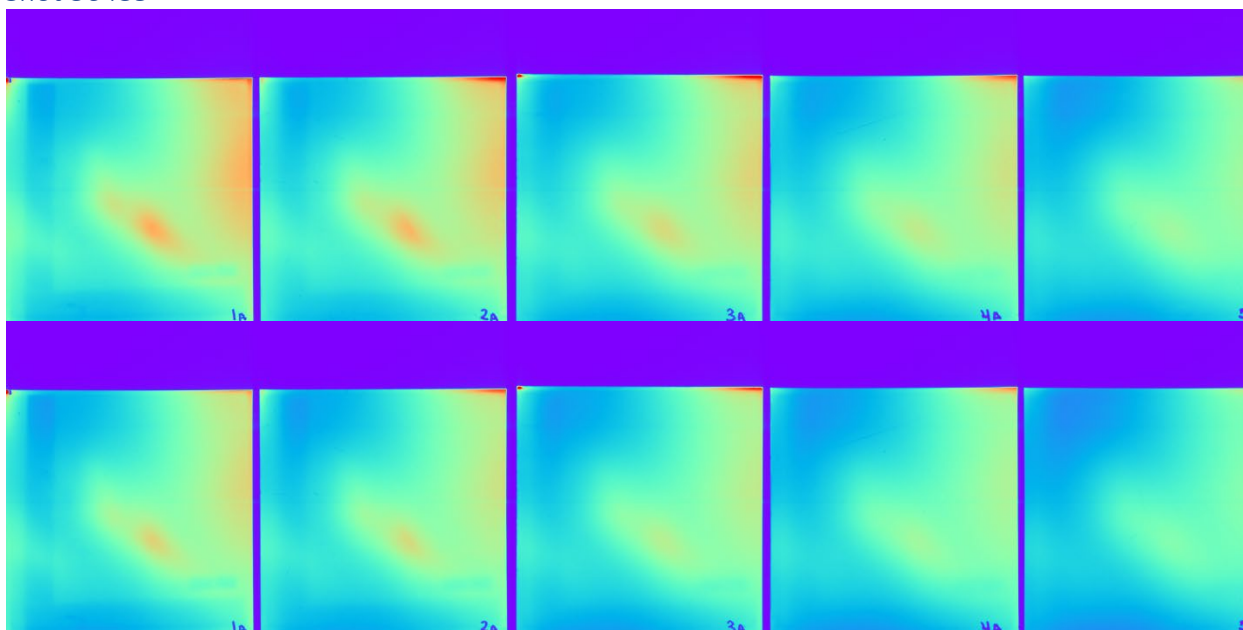


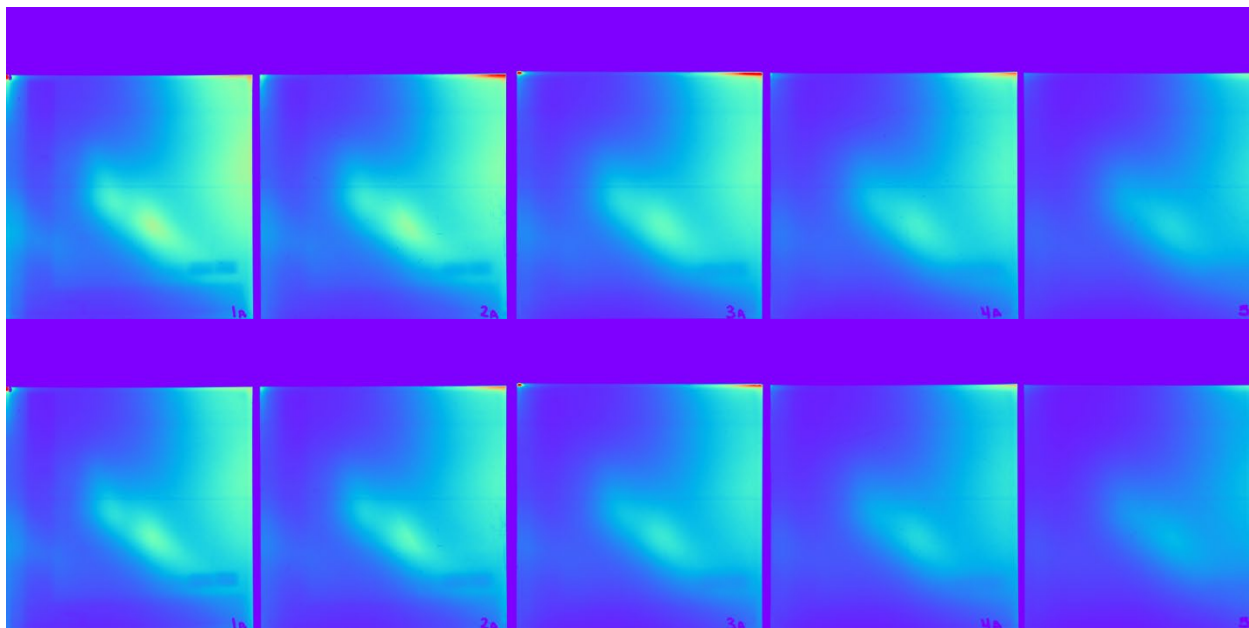




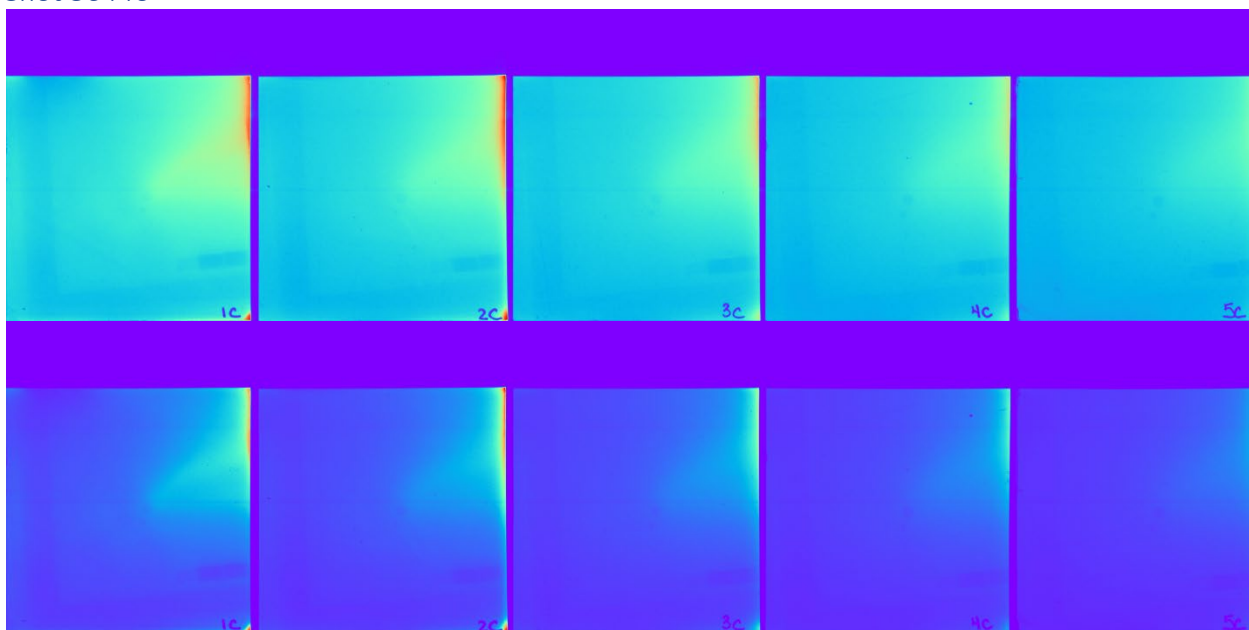


Shot 36439

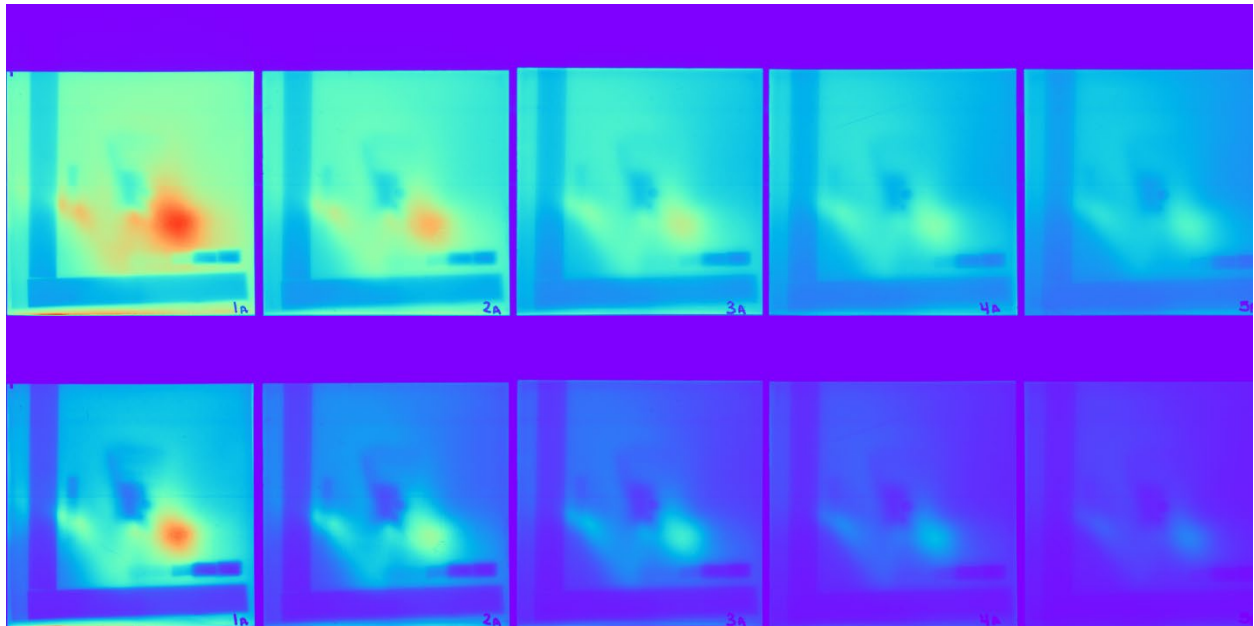




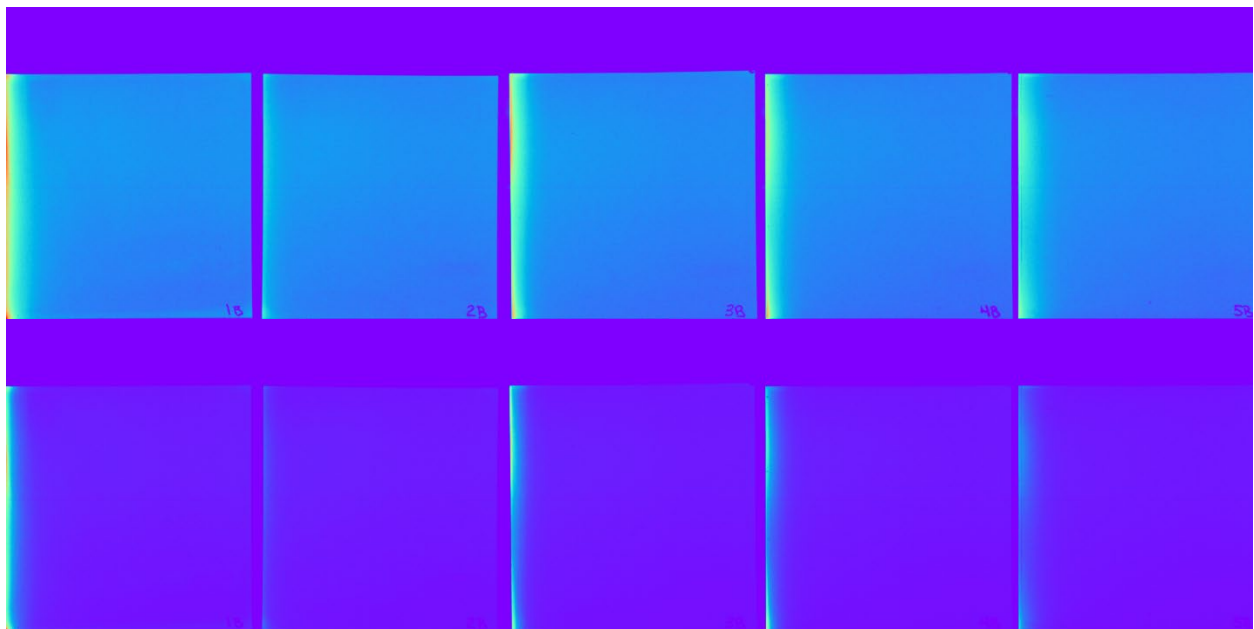
Shot 36440



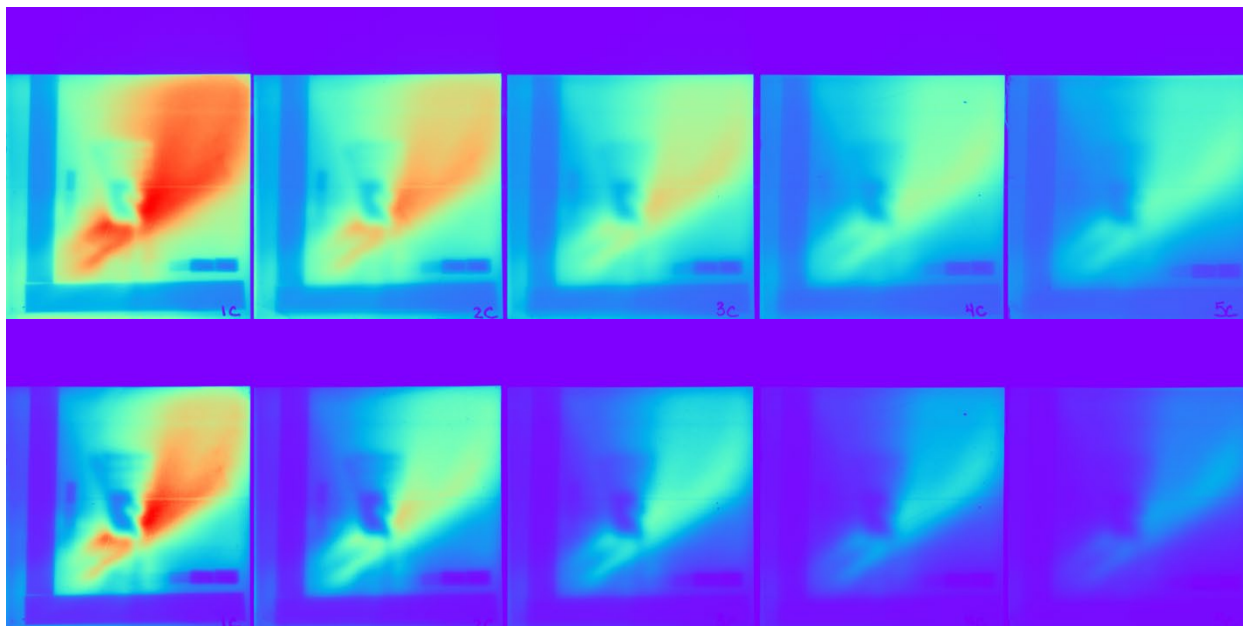
Shot 36441



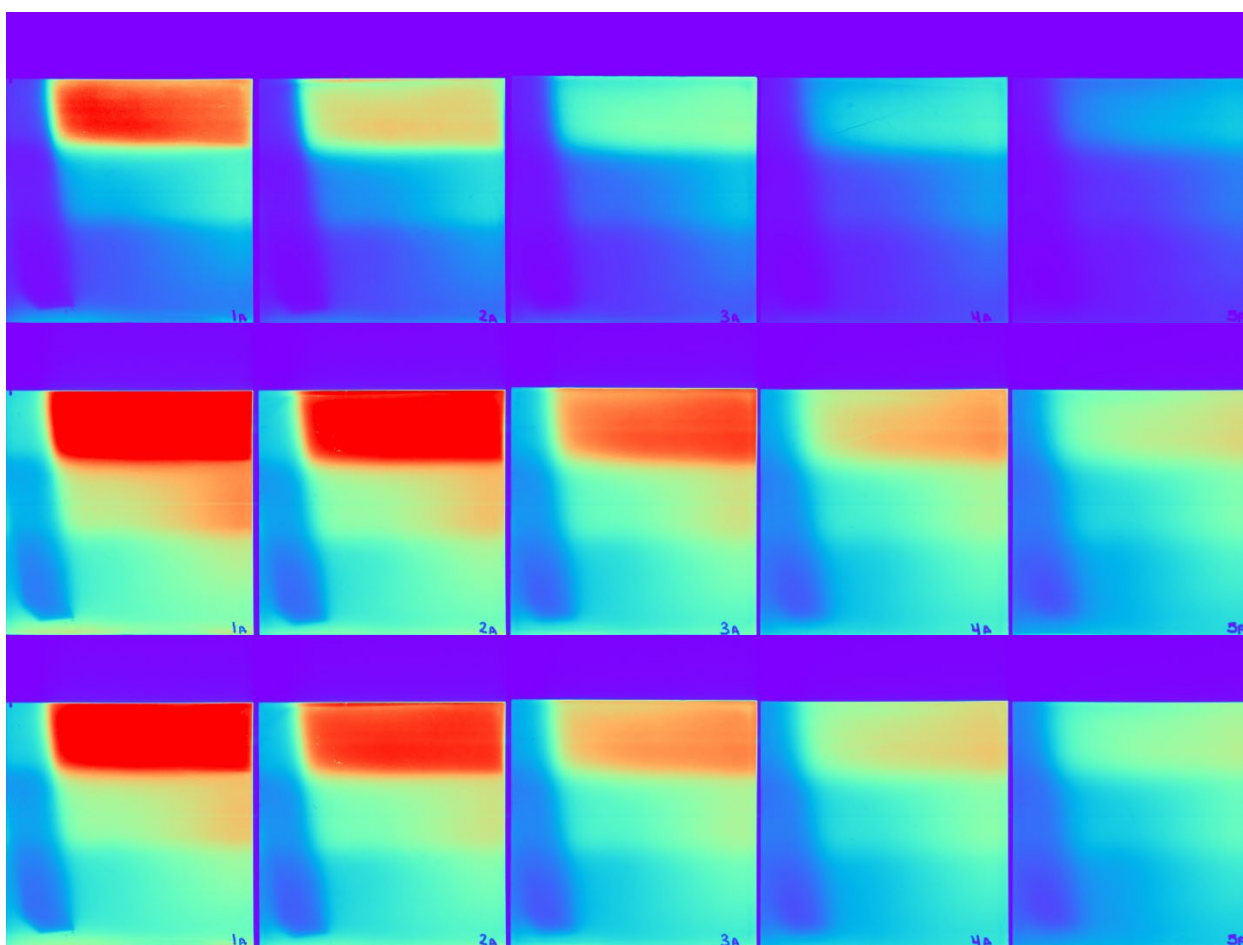
Shot 36442

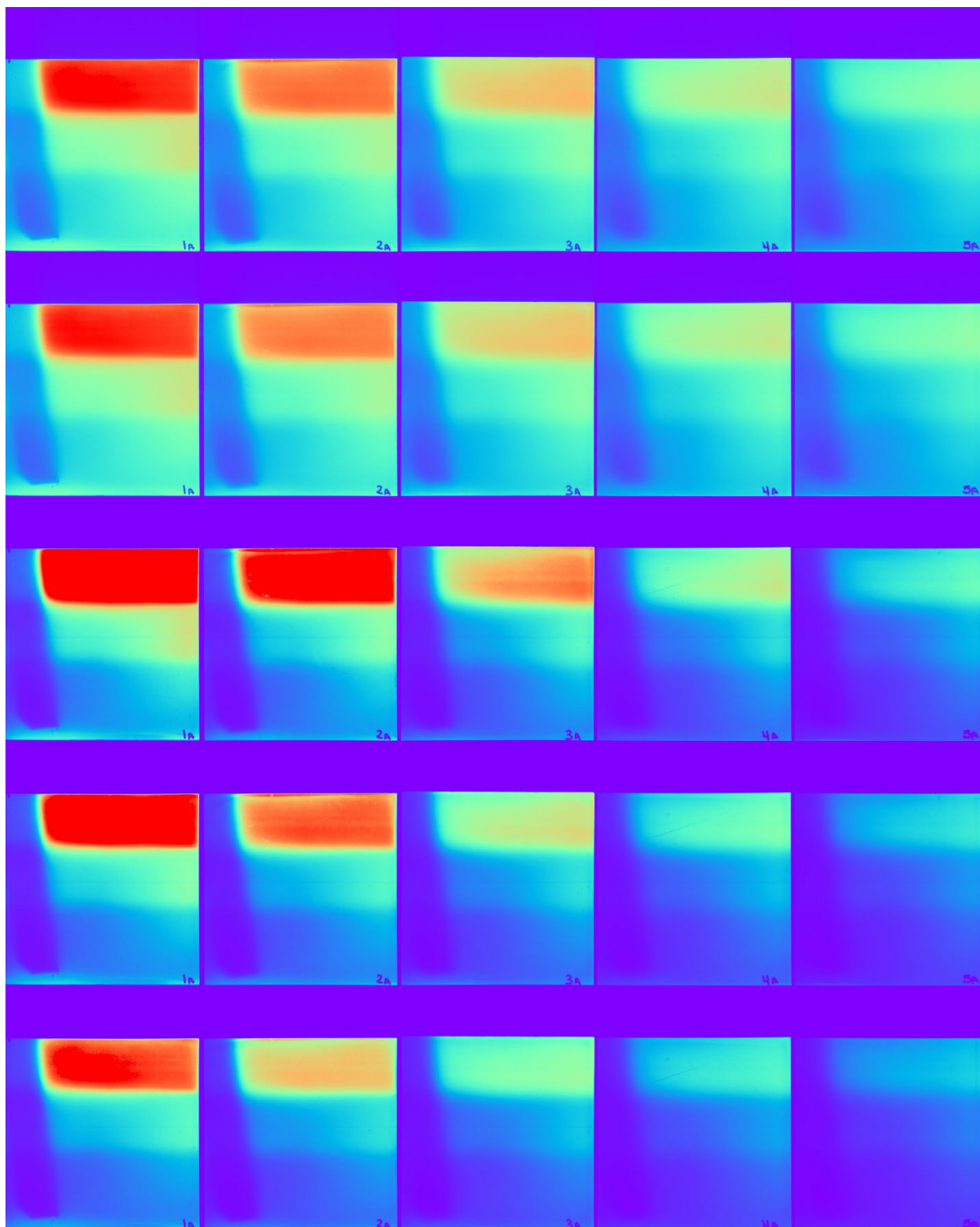


Shot 36443

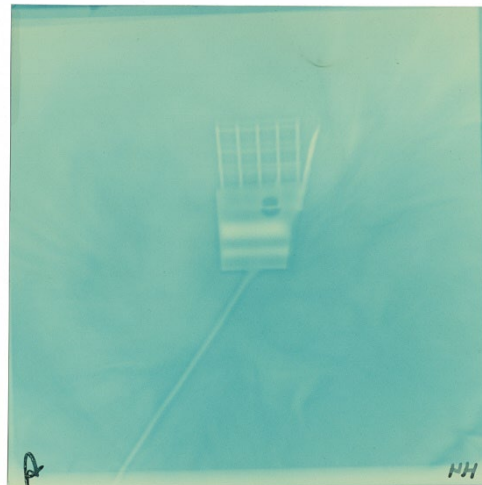
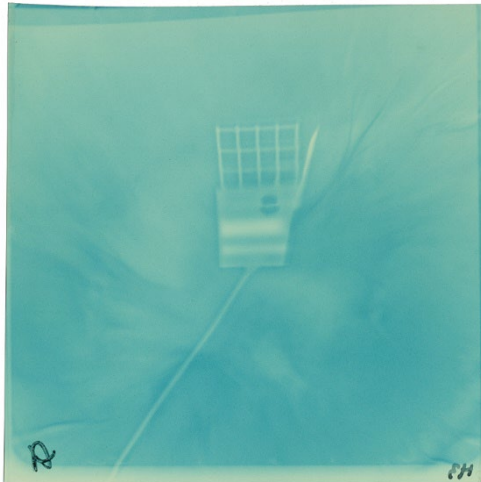
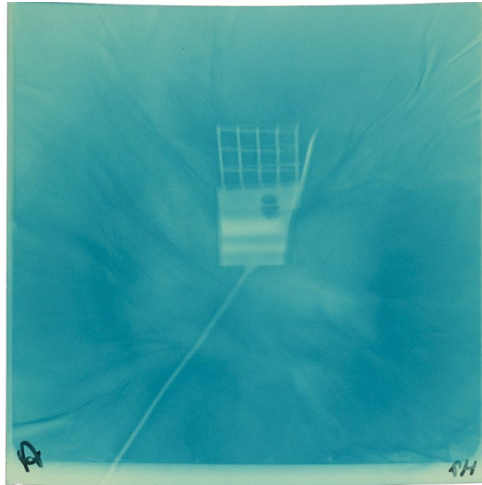
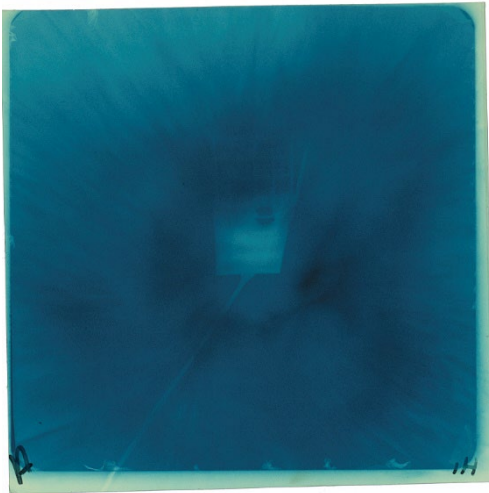


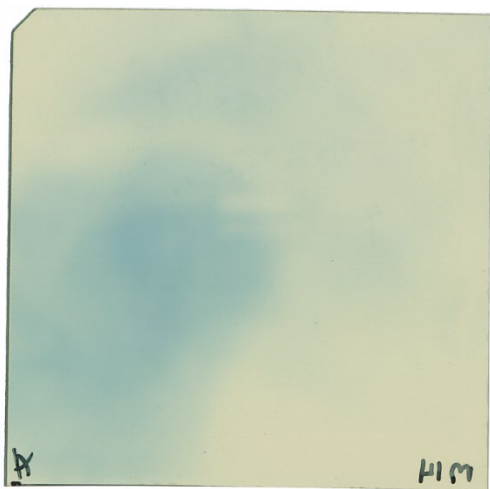
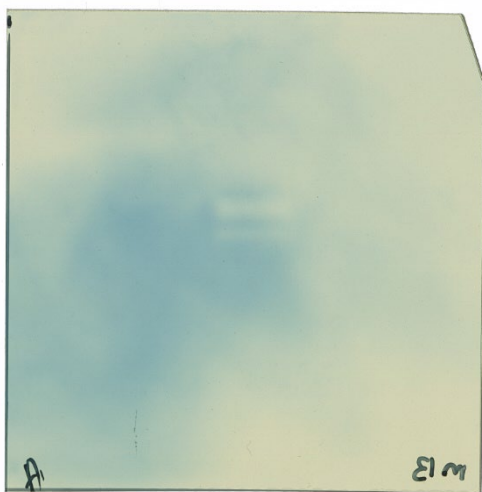
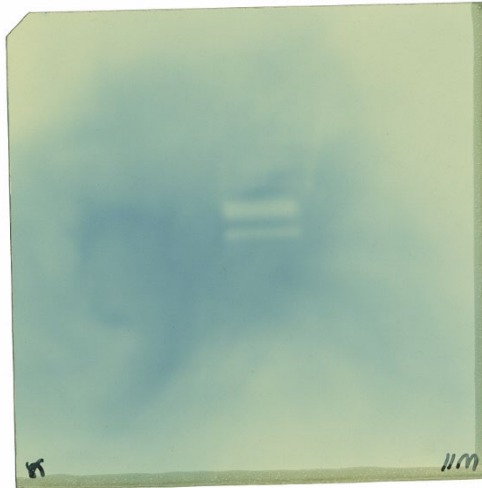
Shot 36444





RCF data
Flatbed
Shot 36435





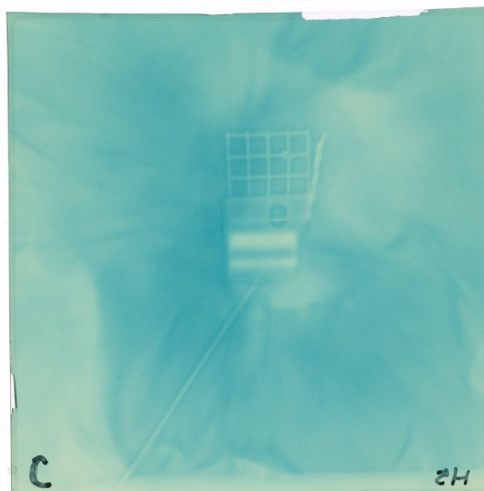
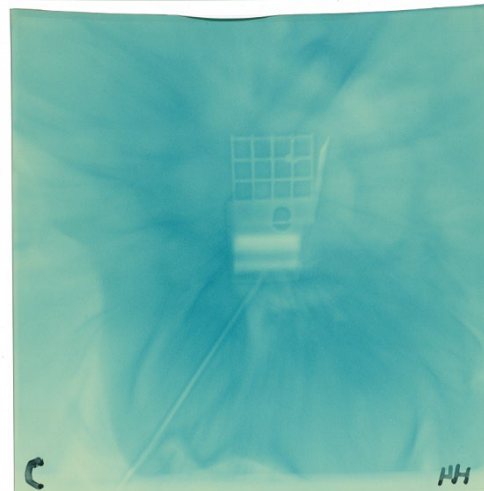
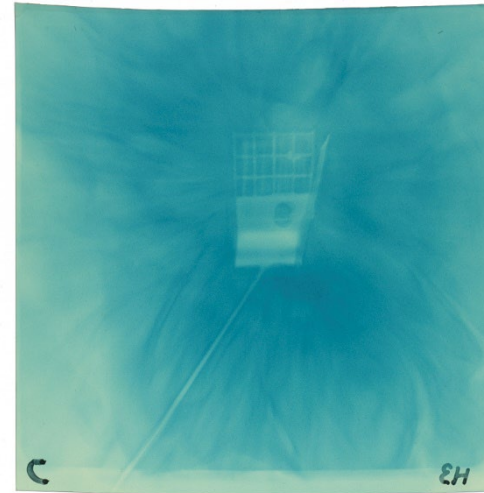
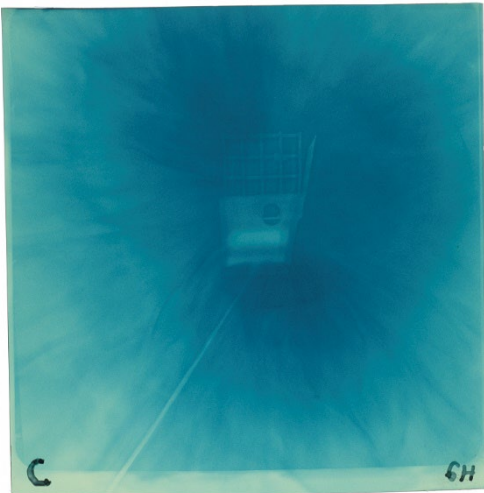
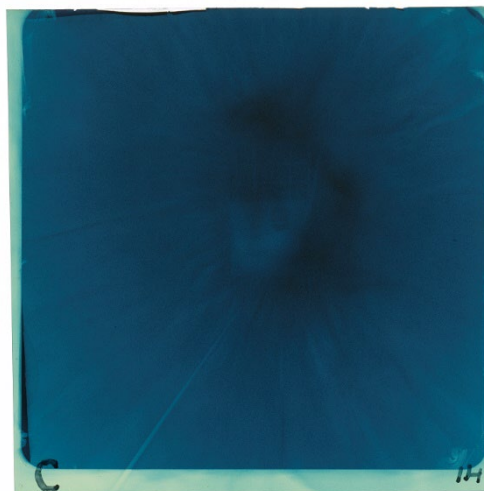
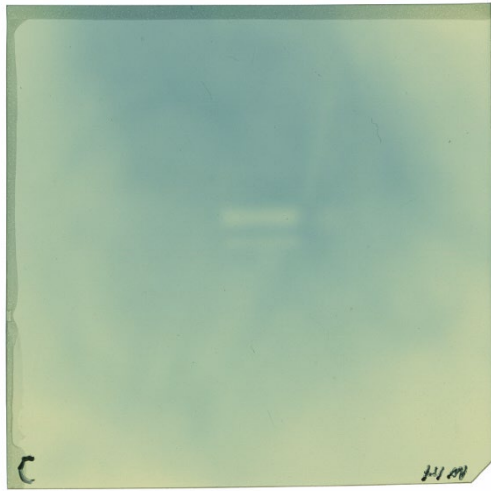
Shot 36436

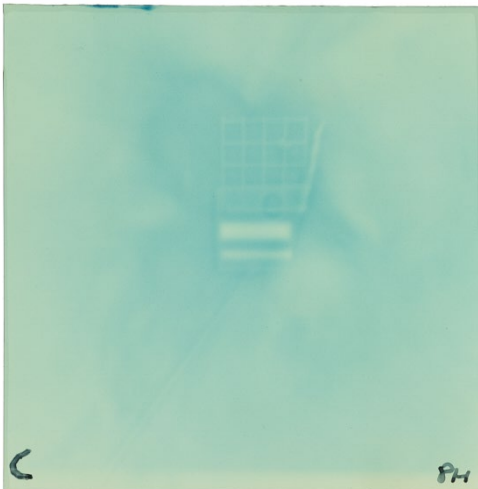
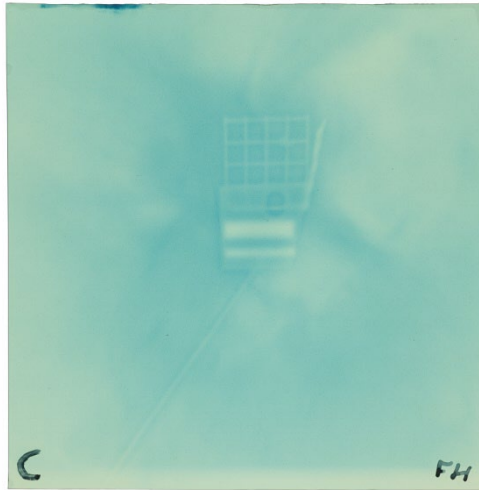
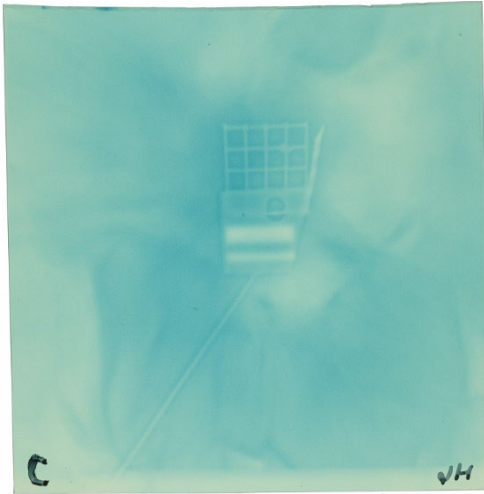


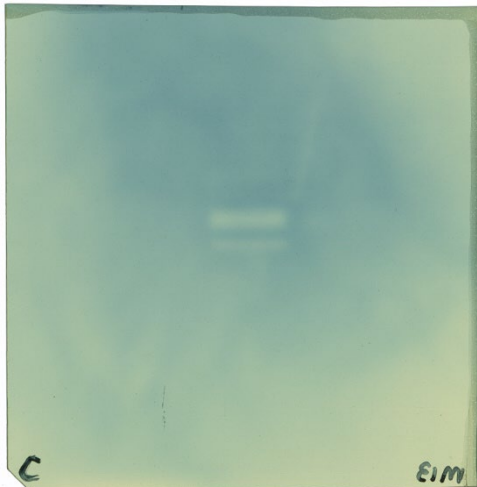
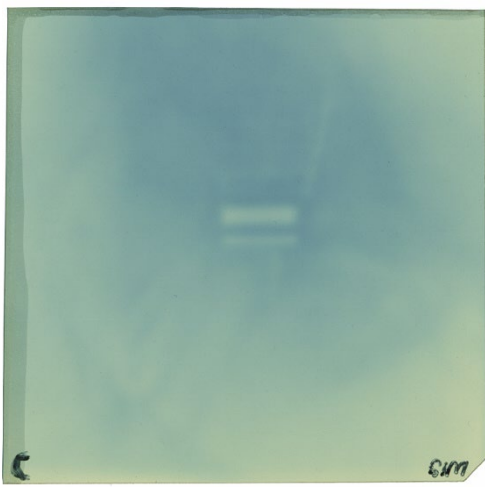
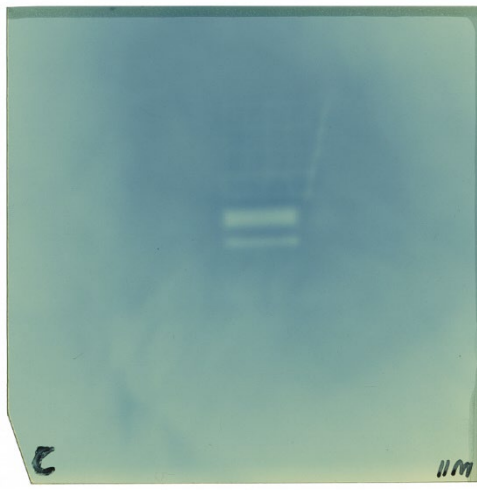
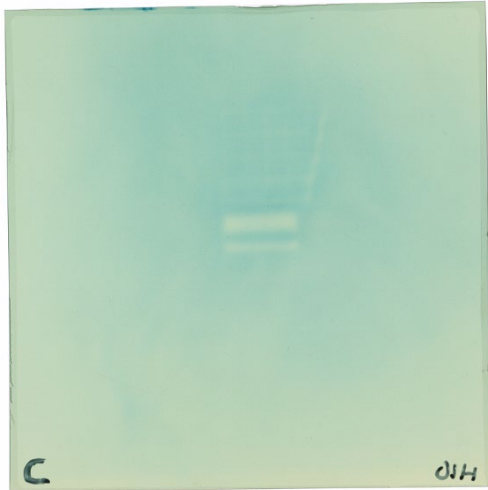




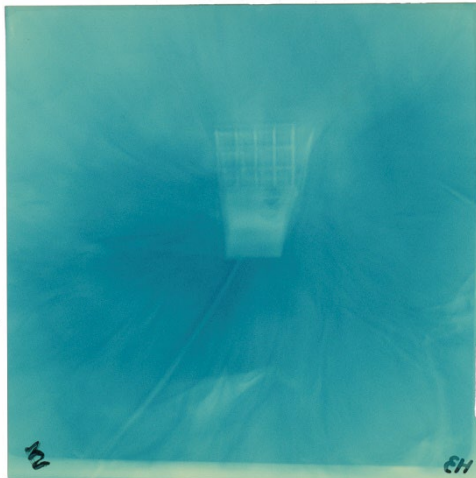
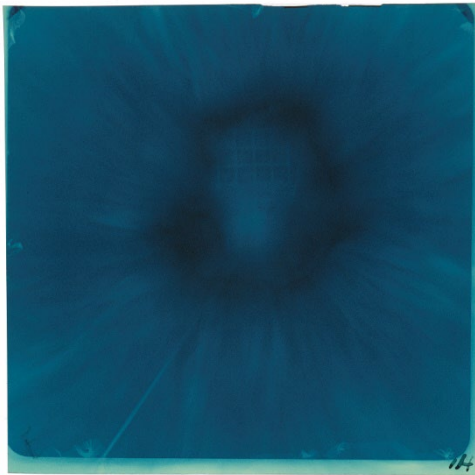
Shot 36437



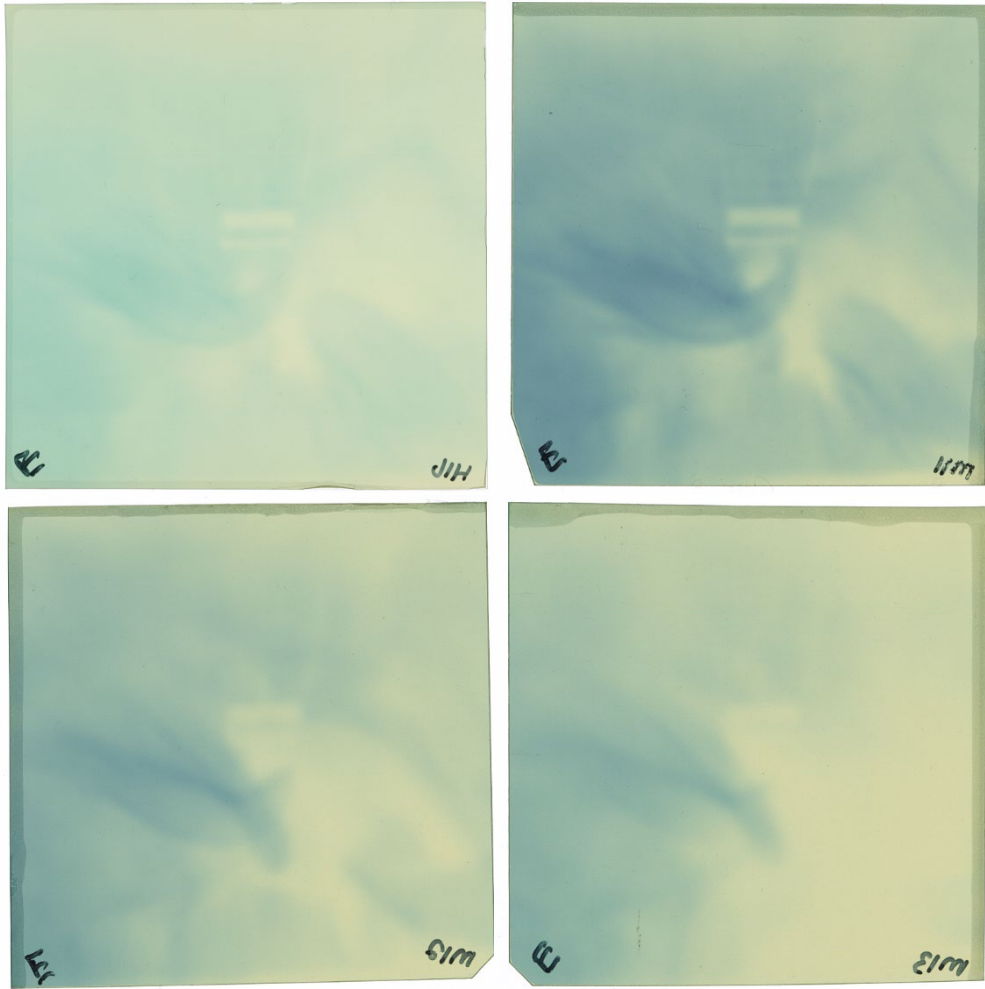




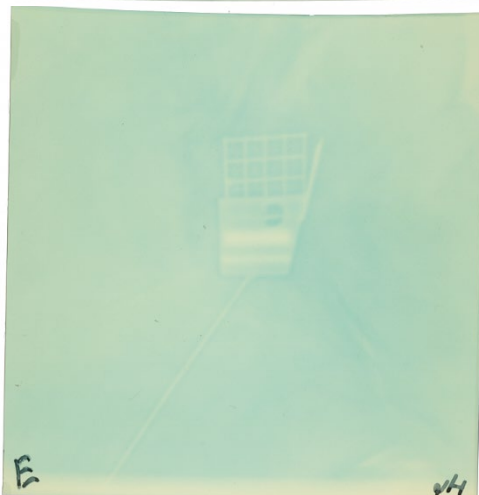
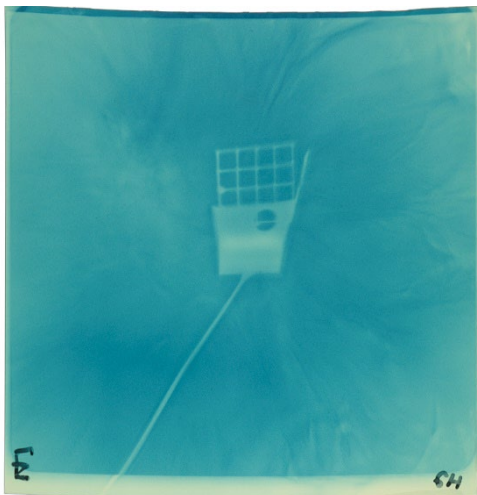
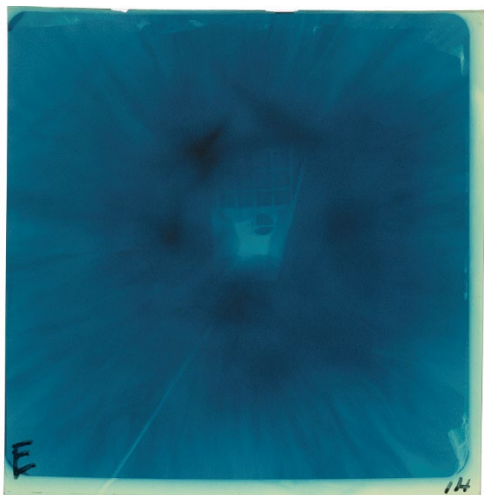
Shot 36438



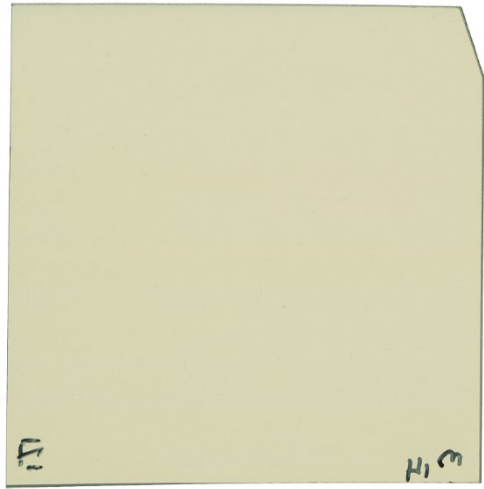
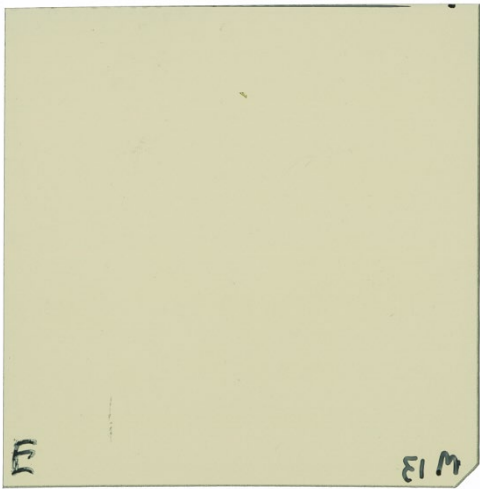




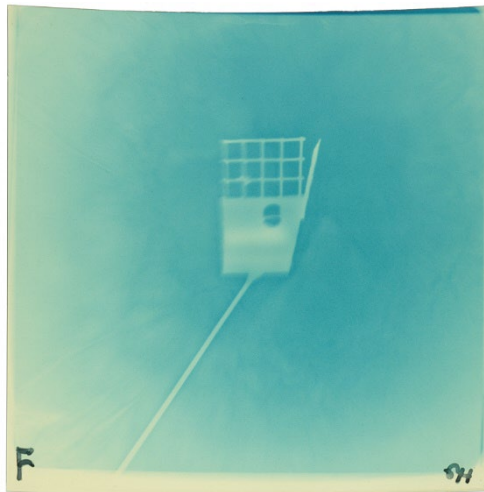
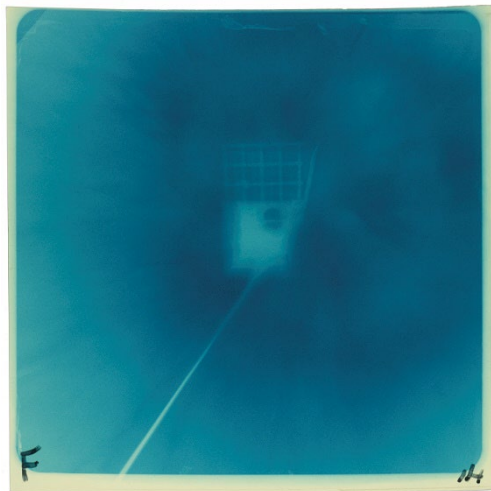
Shot 36439







Shot 36440



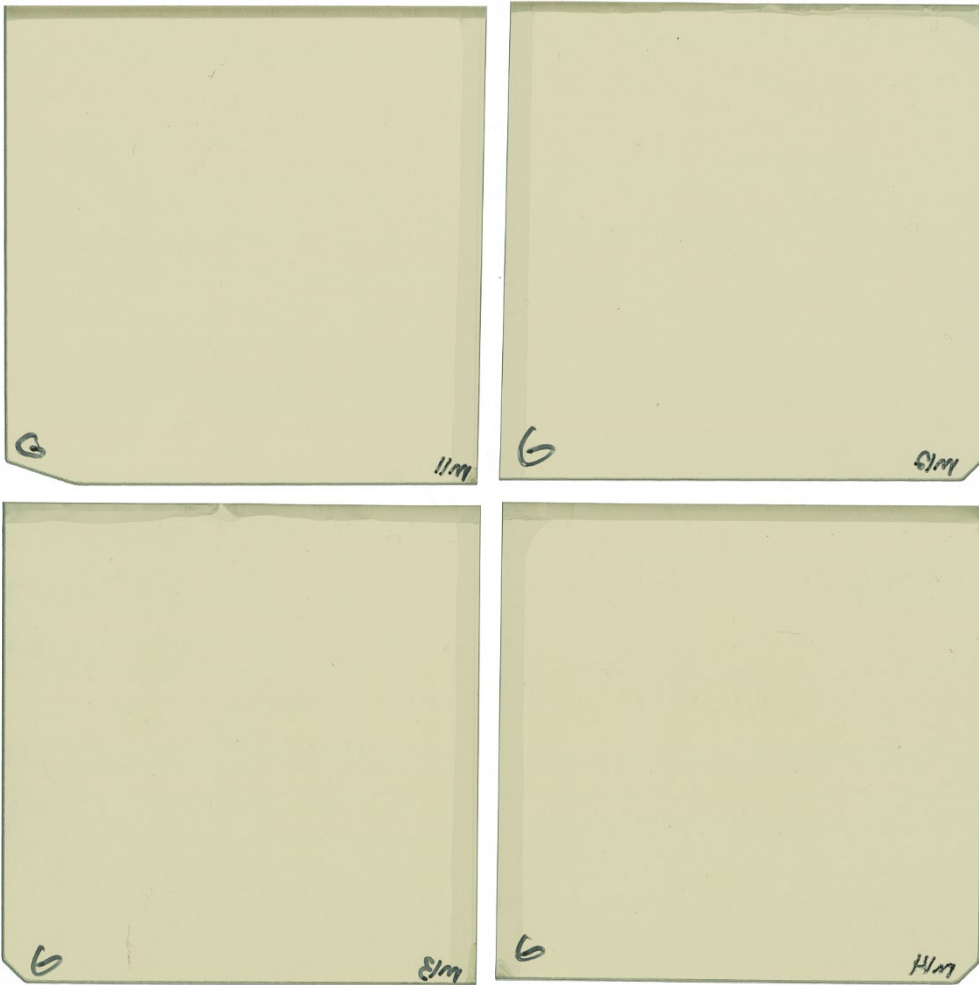




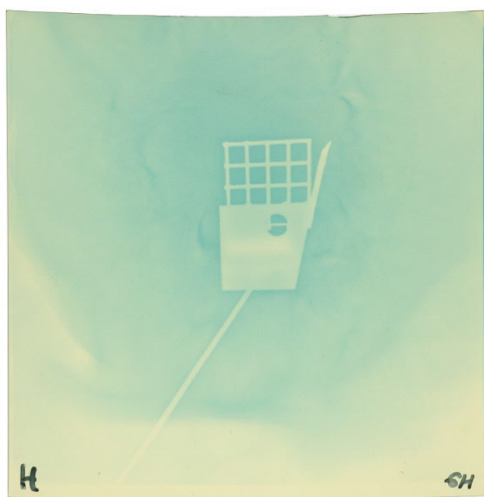
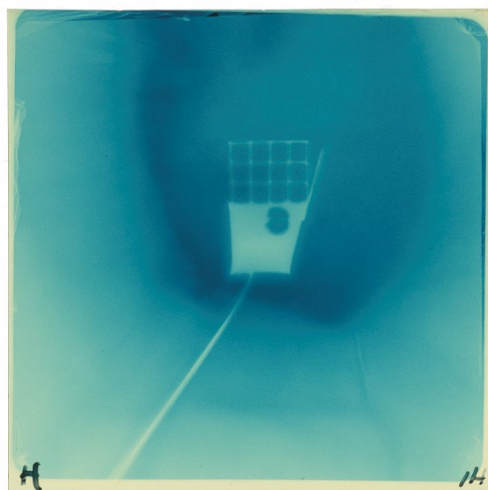
Shot 36441



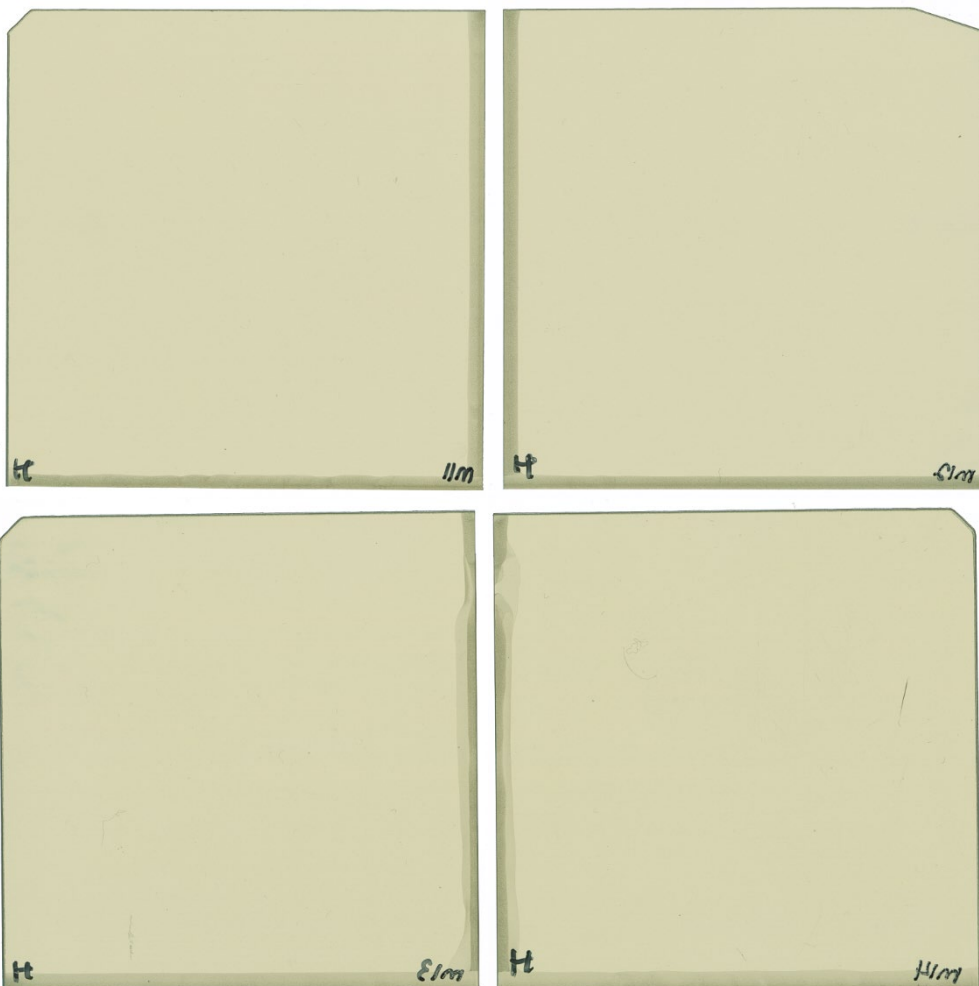




Shot 36442



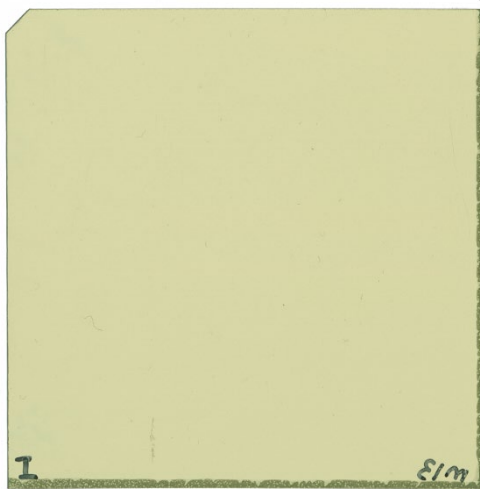
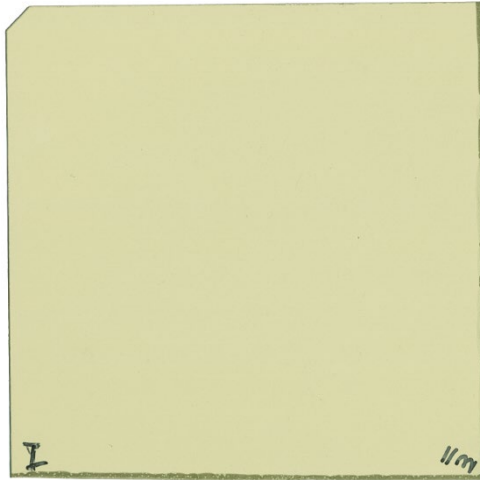




Shot 36443



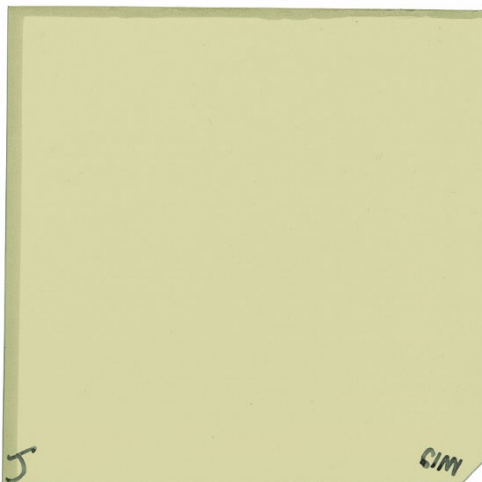




Shot 36444

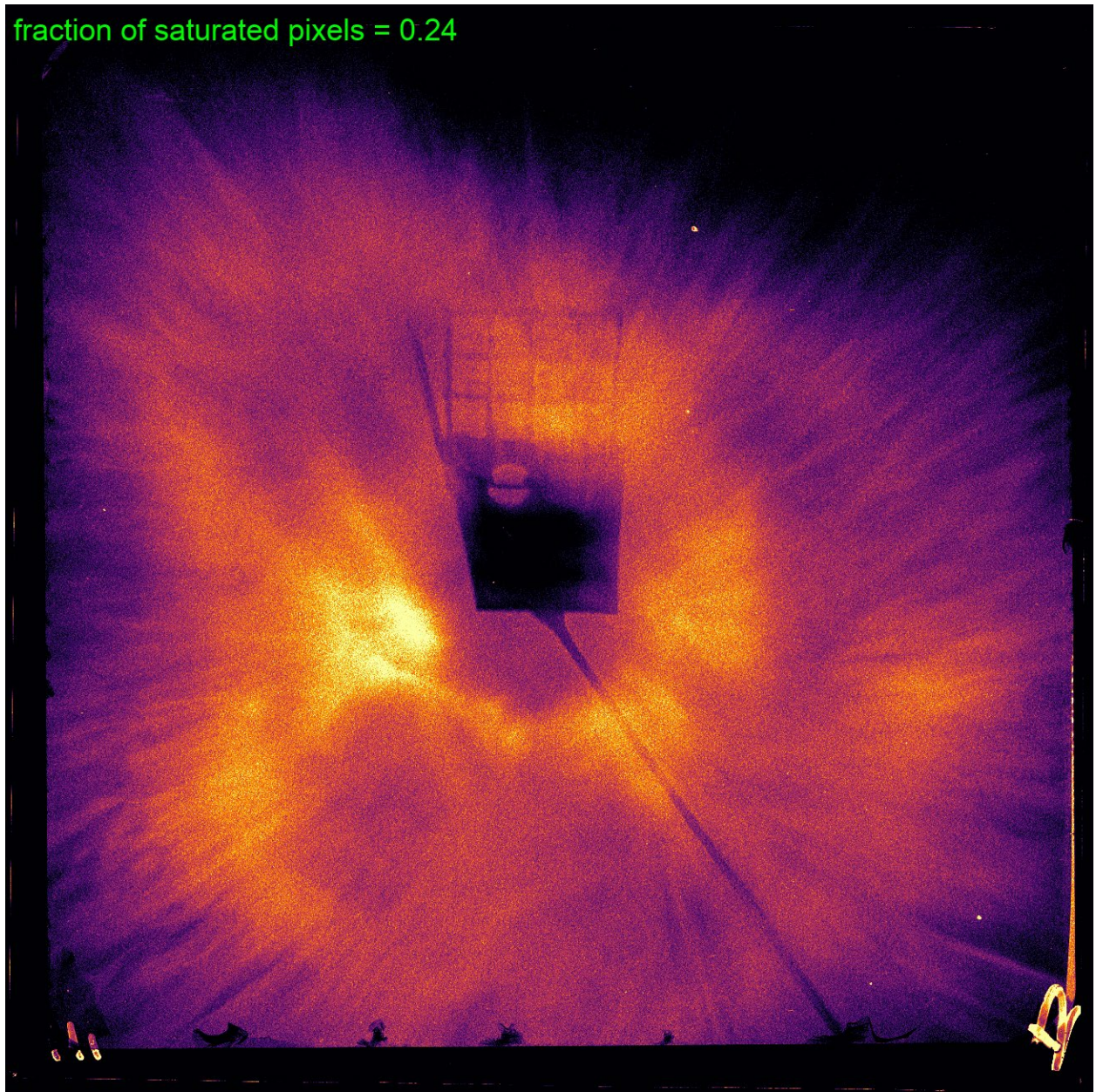




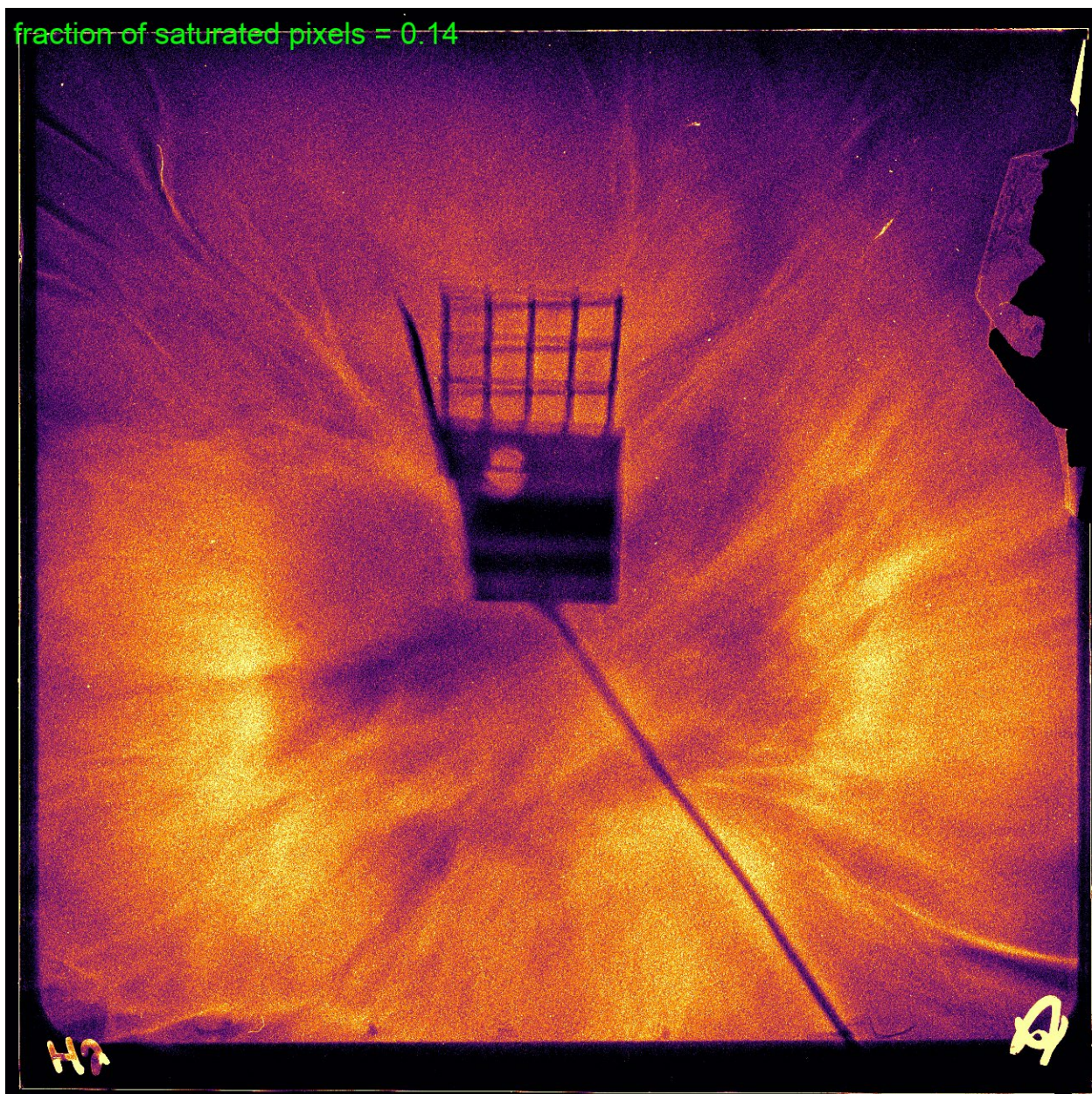


Micro-scanned film
Shot 36435

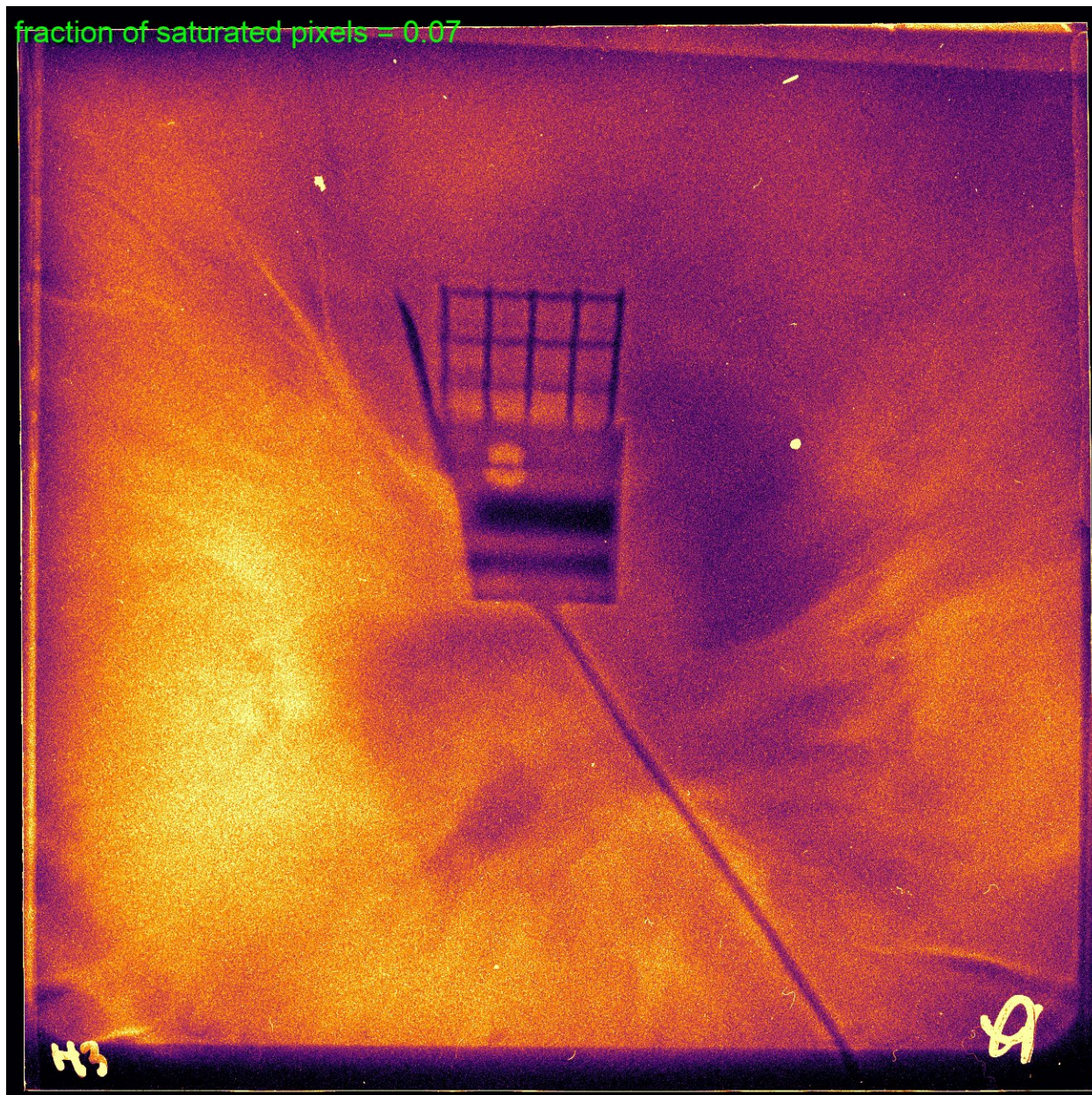
fraction of saturated pixels = 0.24



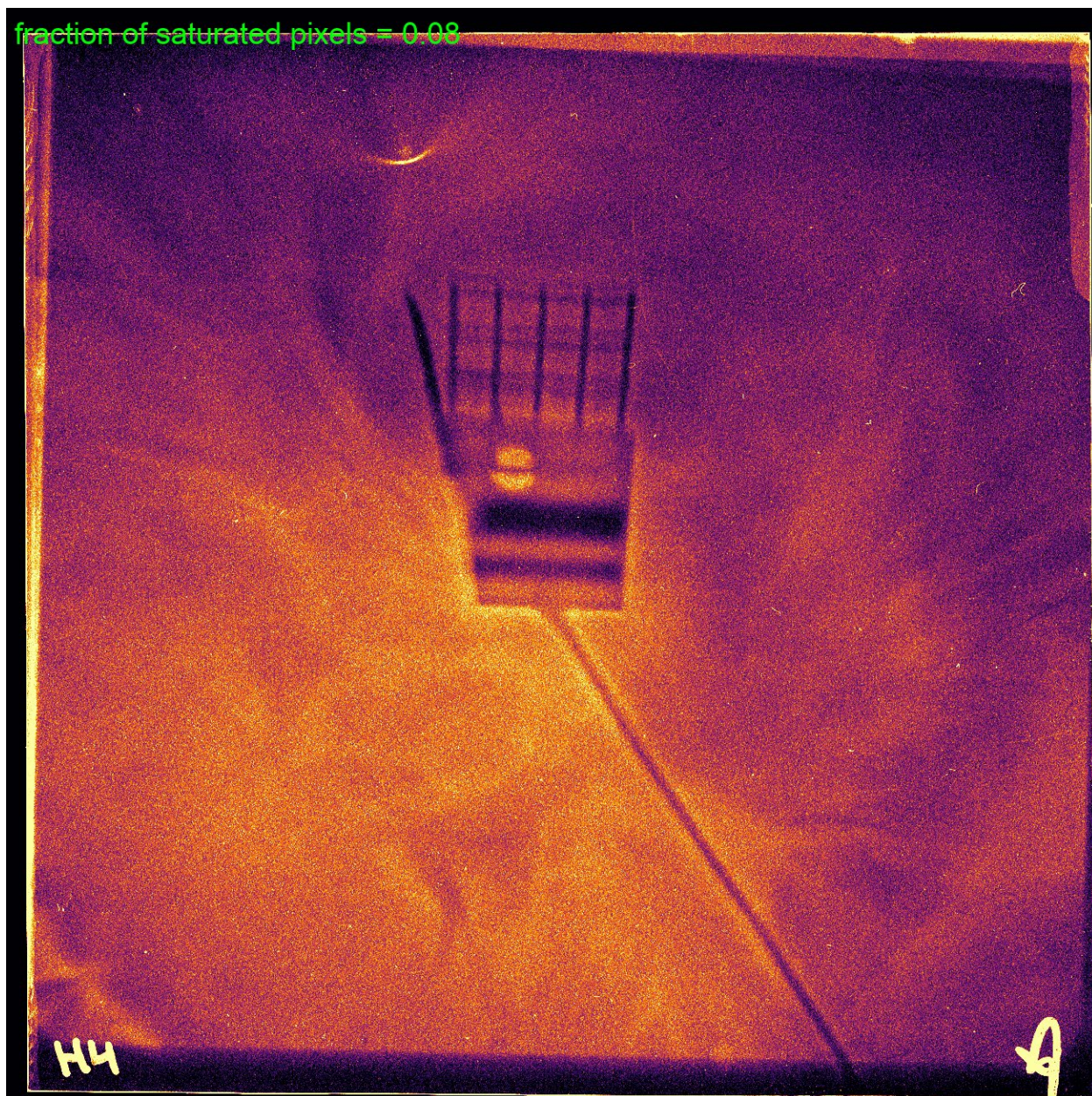
fraction of saturated pixels = 0.14



fraction of saturated pixels = 0.07



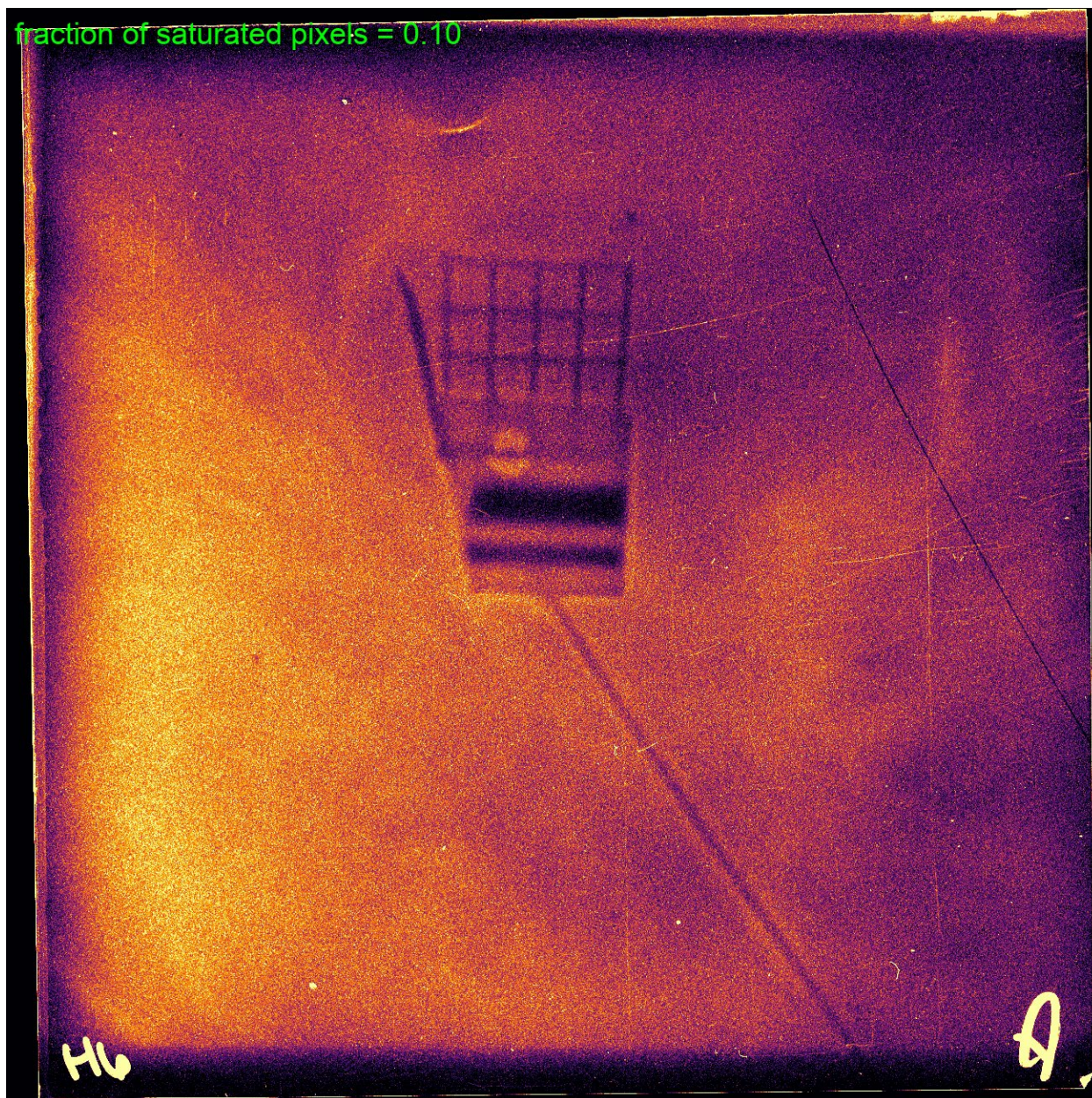
fraction of saturated pixels = 0.08

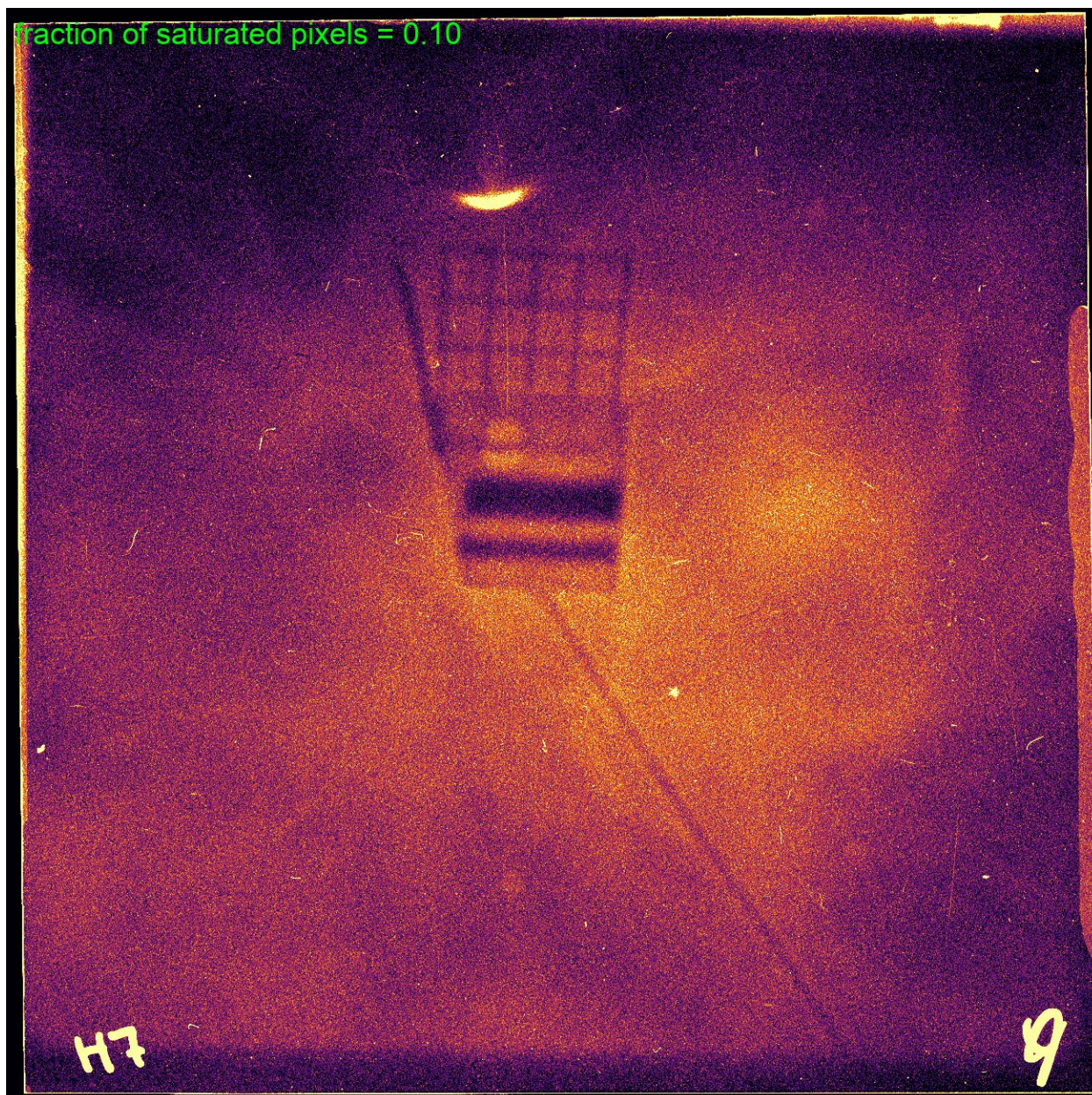


fraction of saturated pixels = 0.08

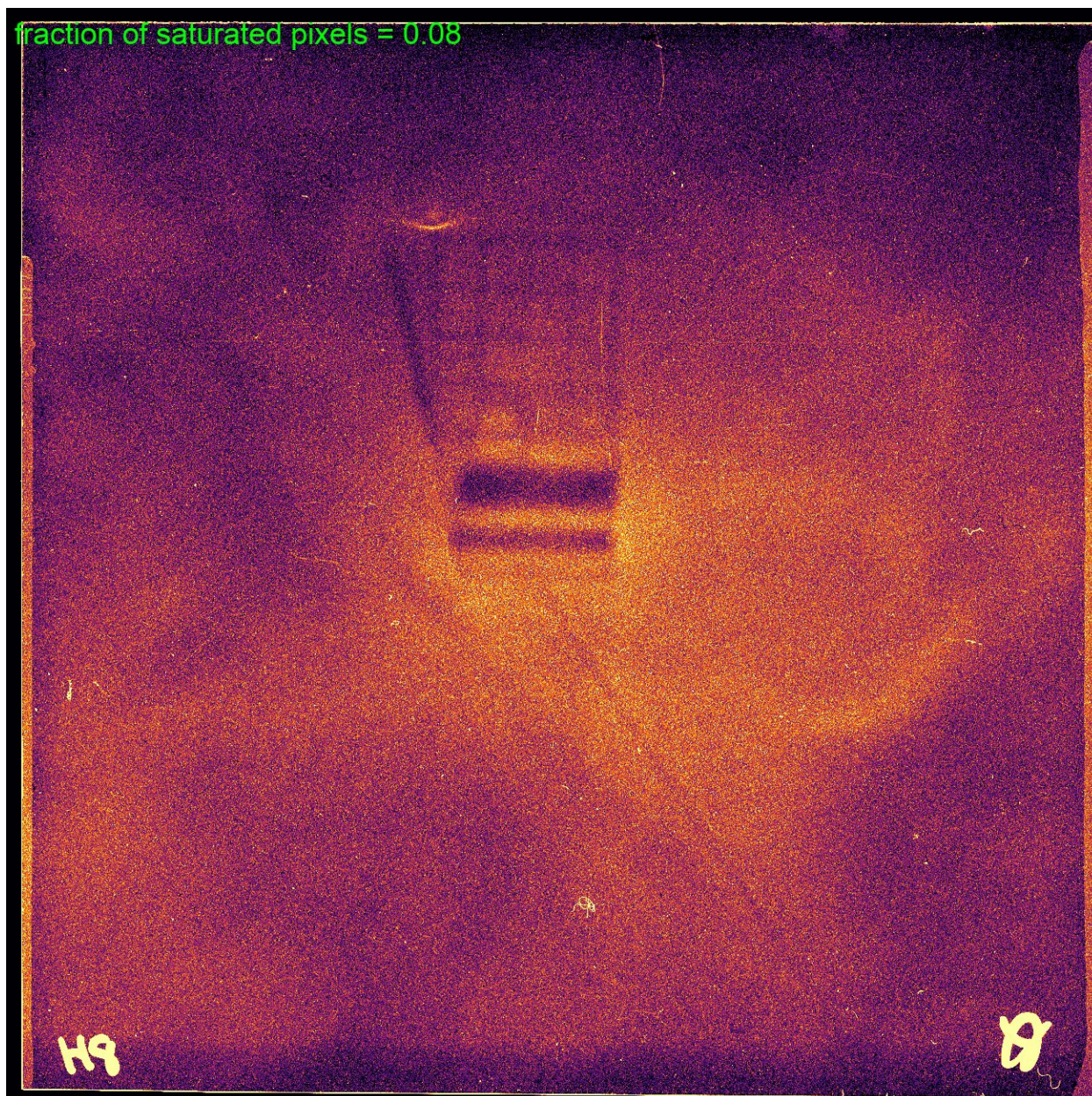


fraction of saturated pixels = 0.10

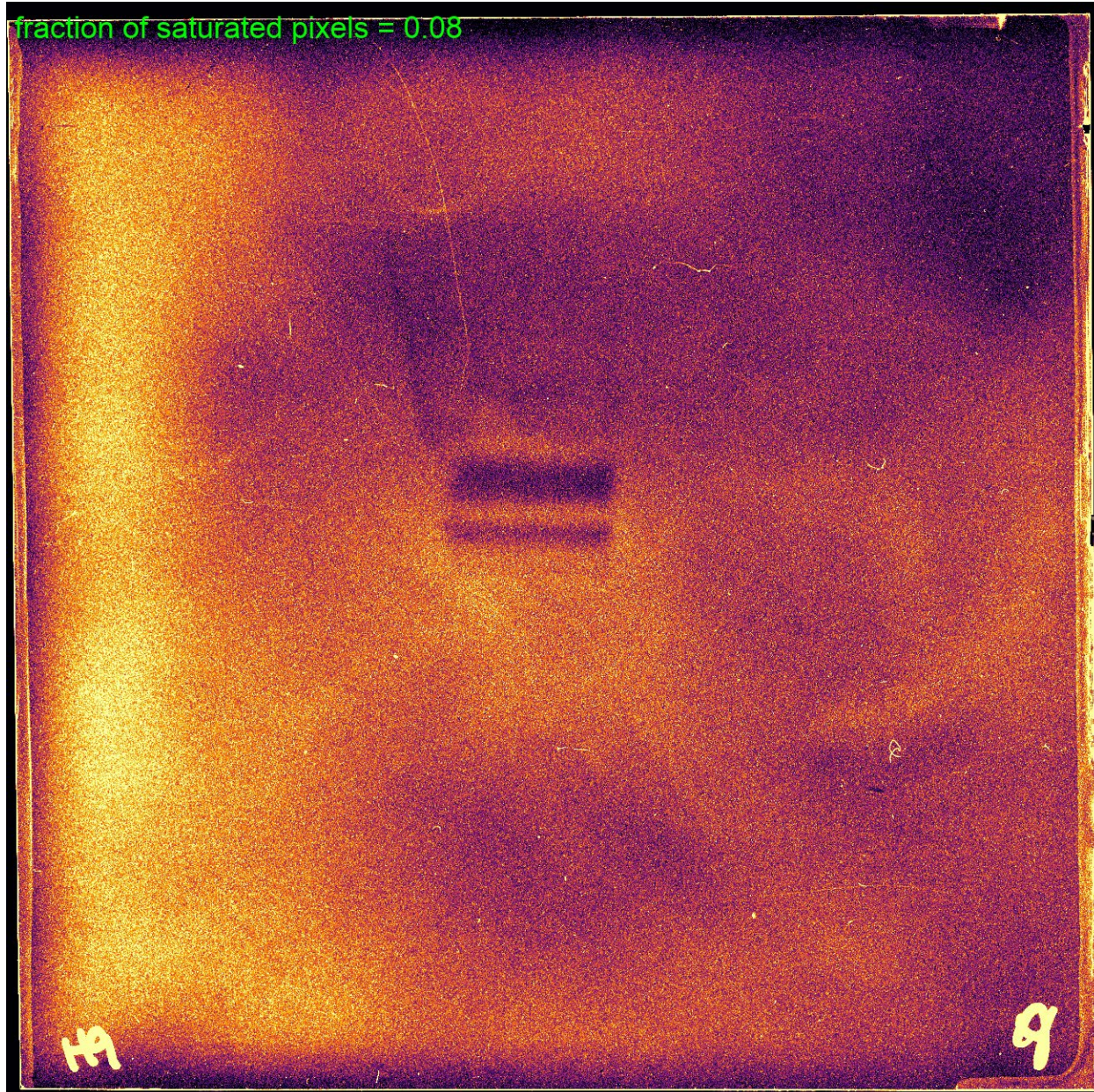




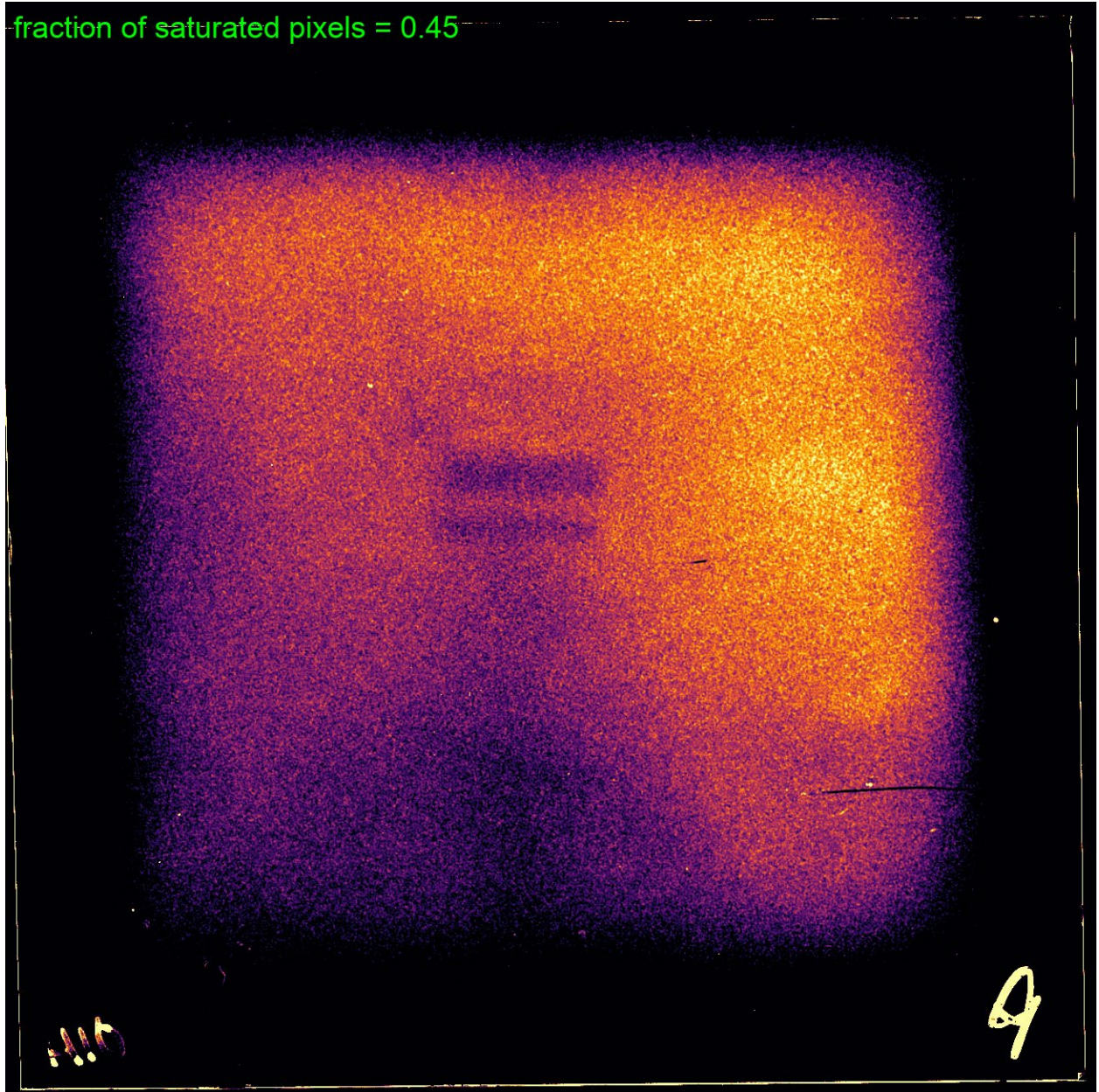
fraction of saturated pixels = 0.08



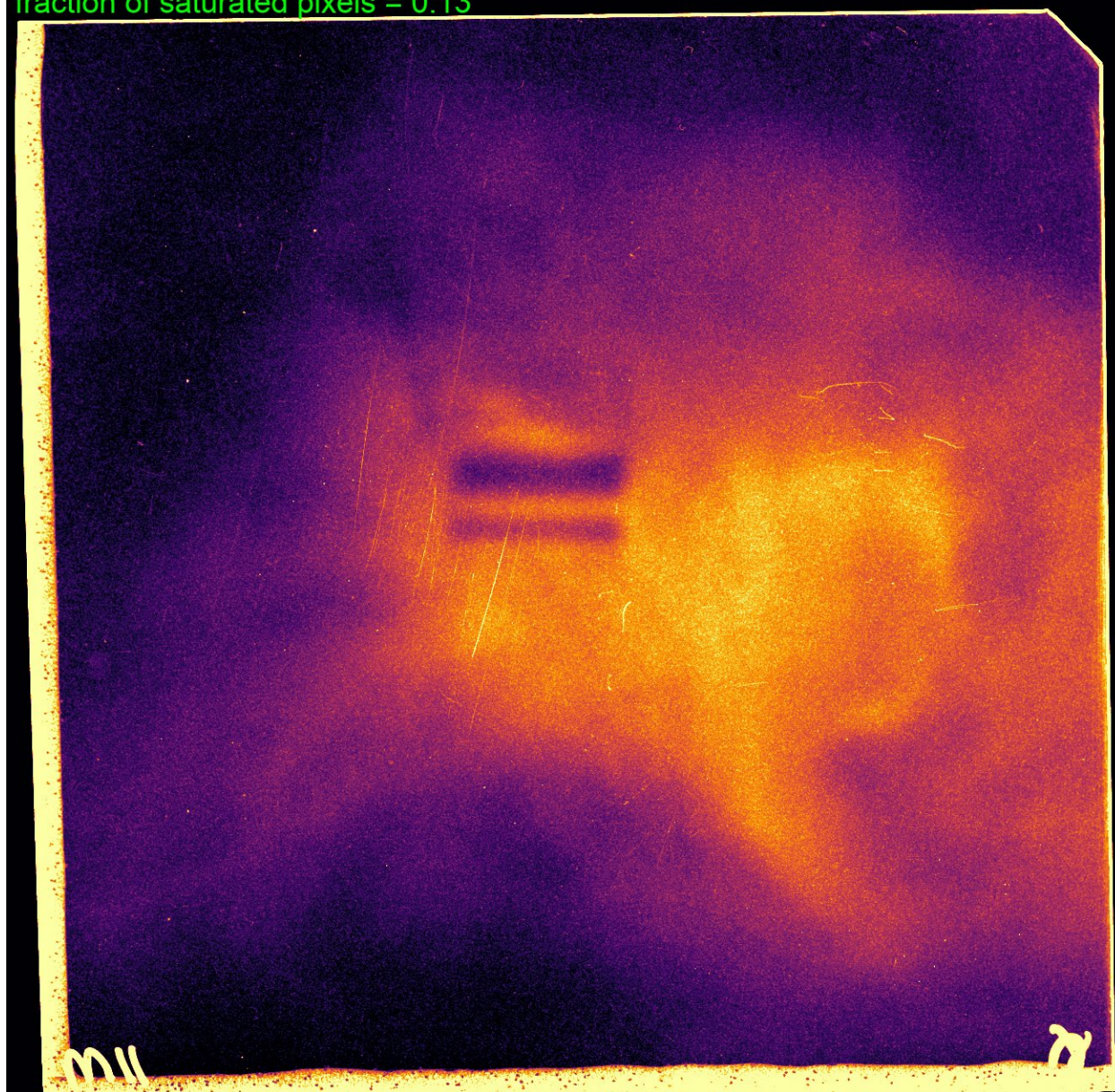
fraction of saturated pixels = 0.08



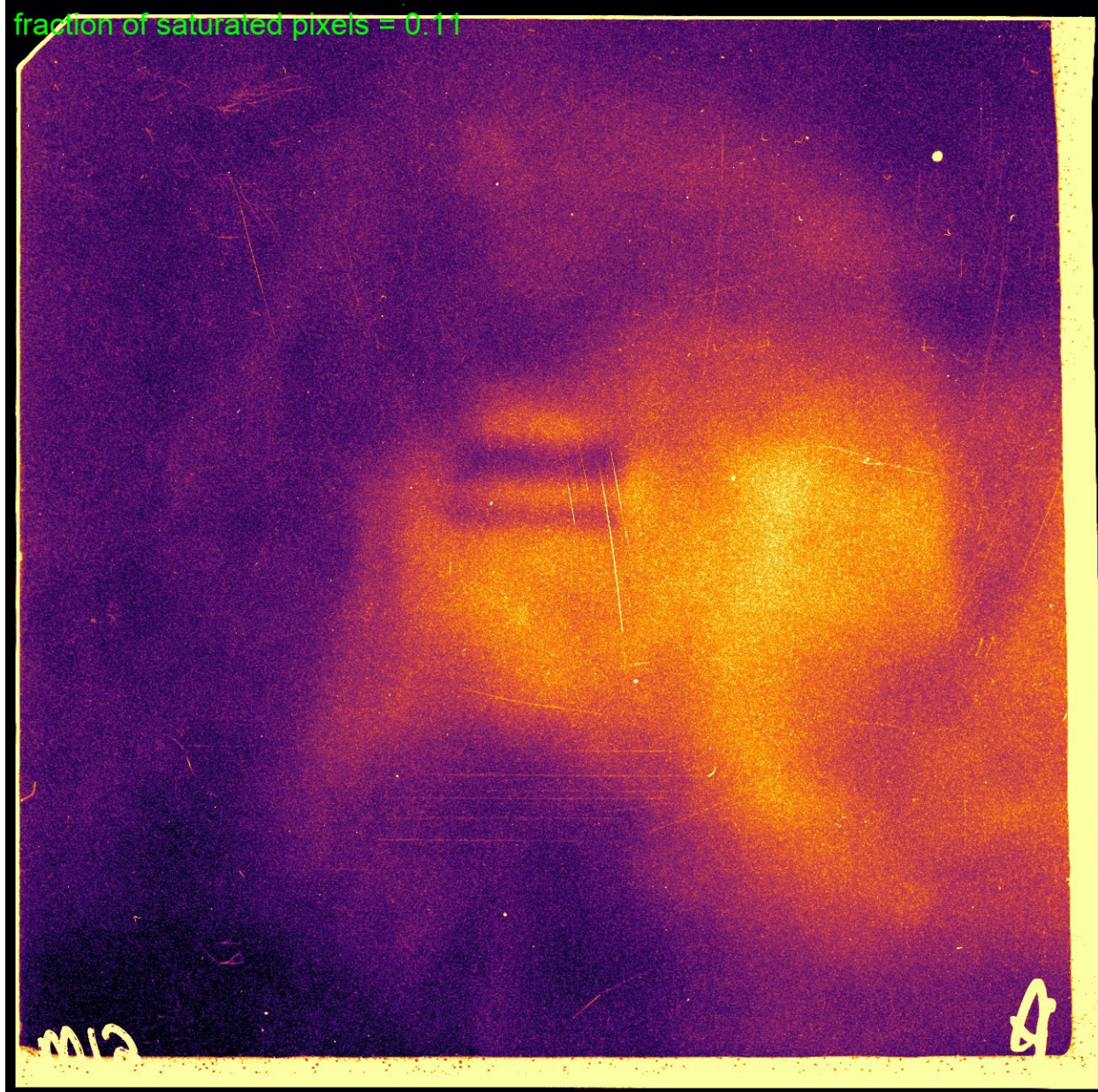
-fraction of saturated pixels = 0.45



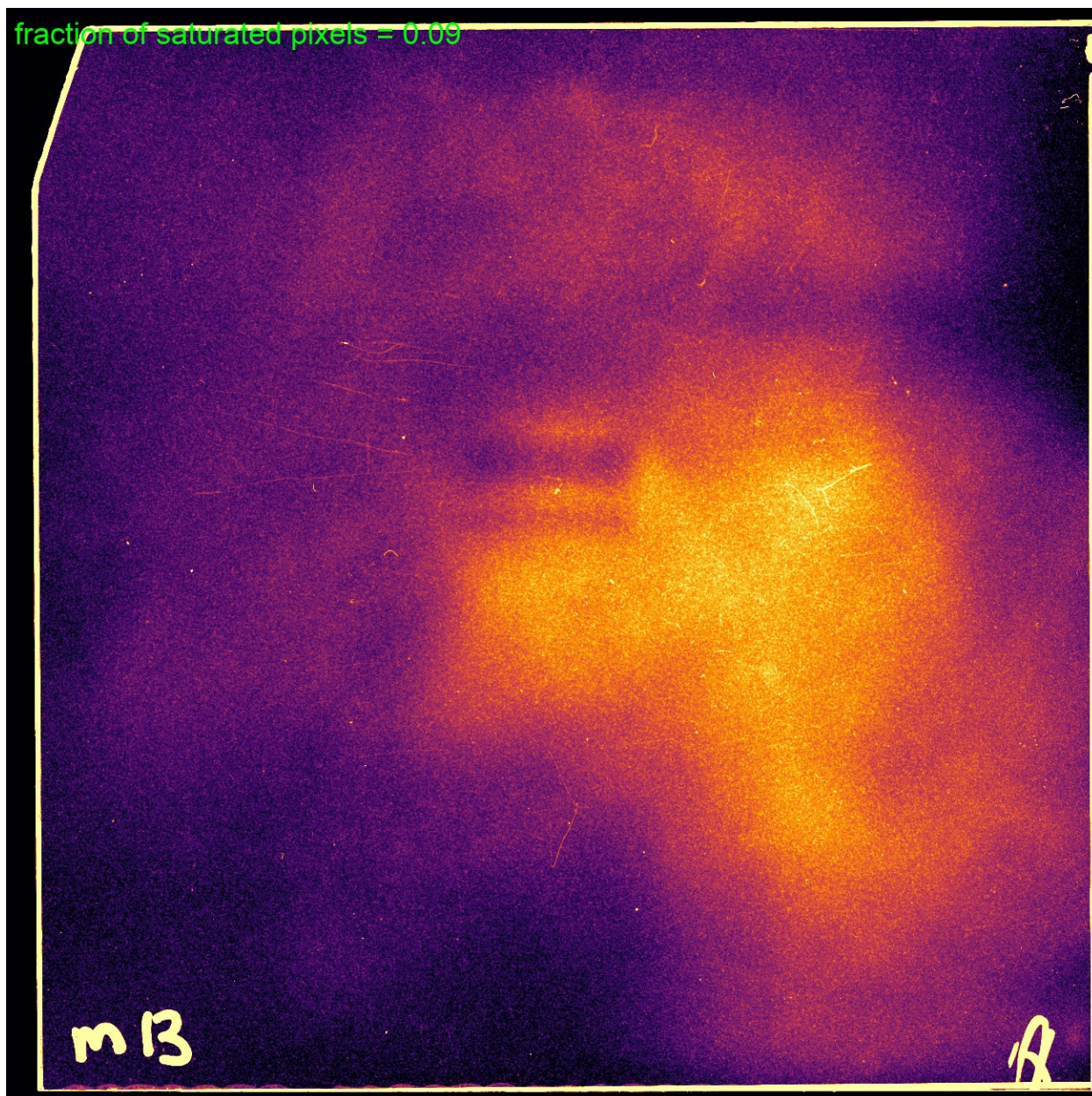
fraction of saturated pixels = 0.13



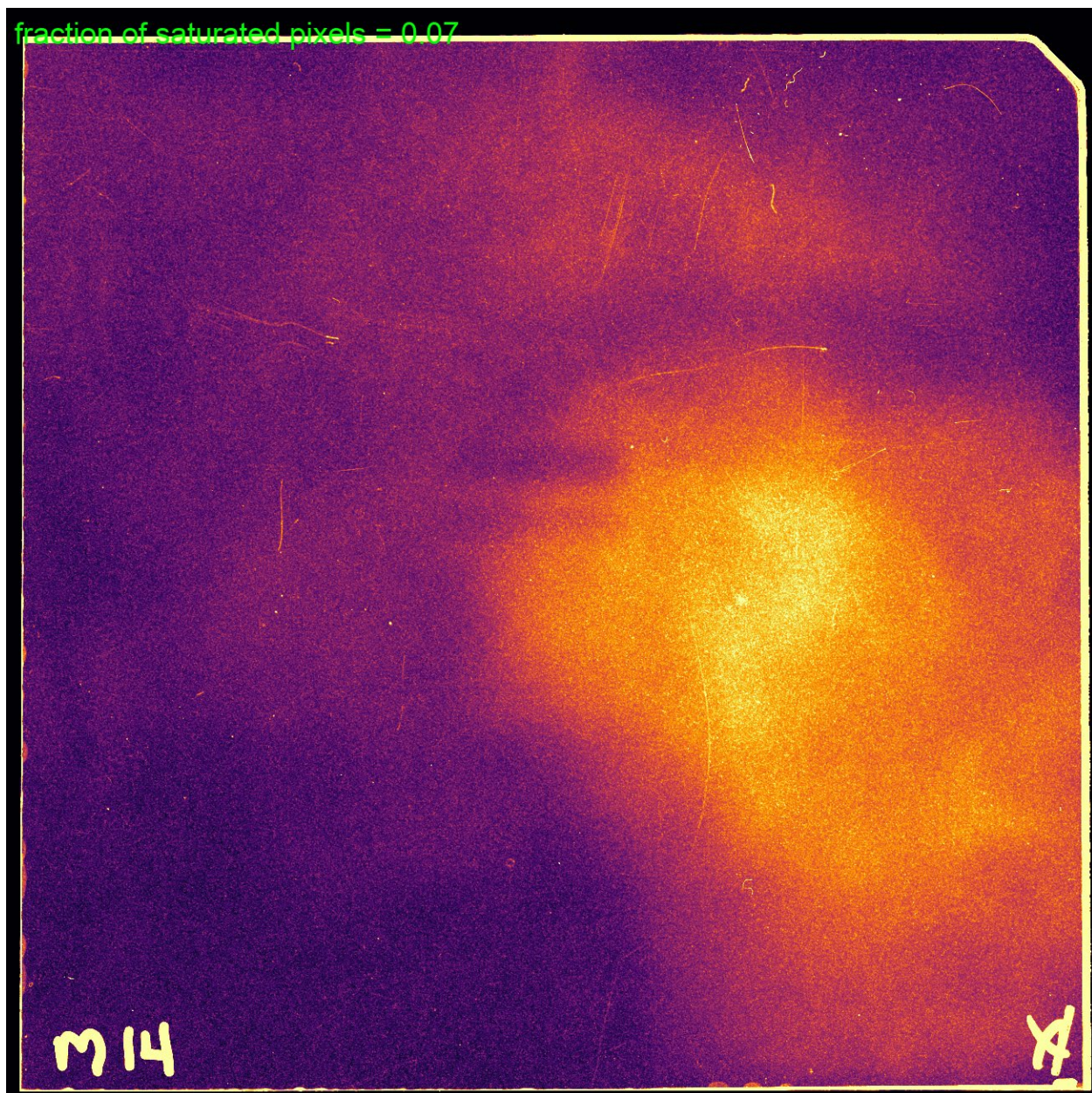
fraction of saturated pixels = 0.11



fraction of saturated pixels = 0.09

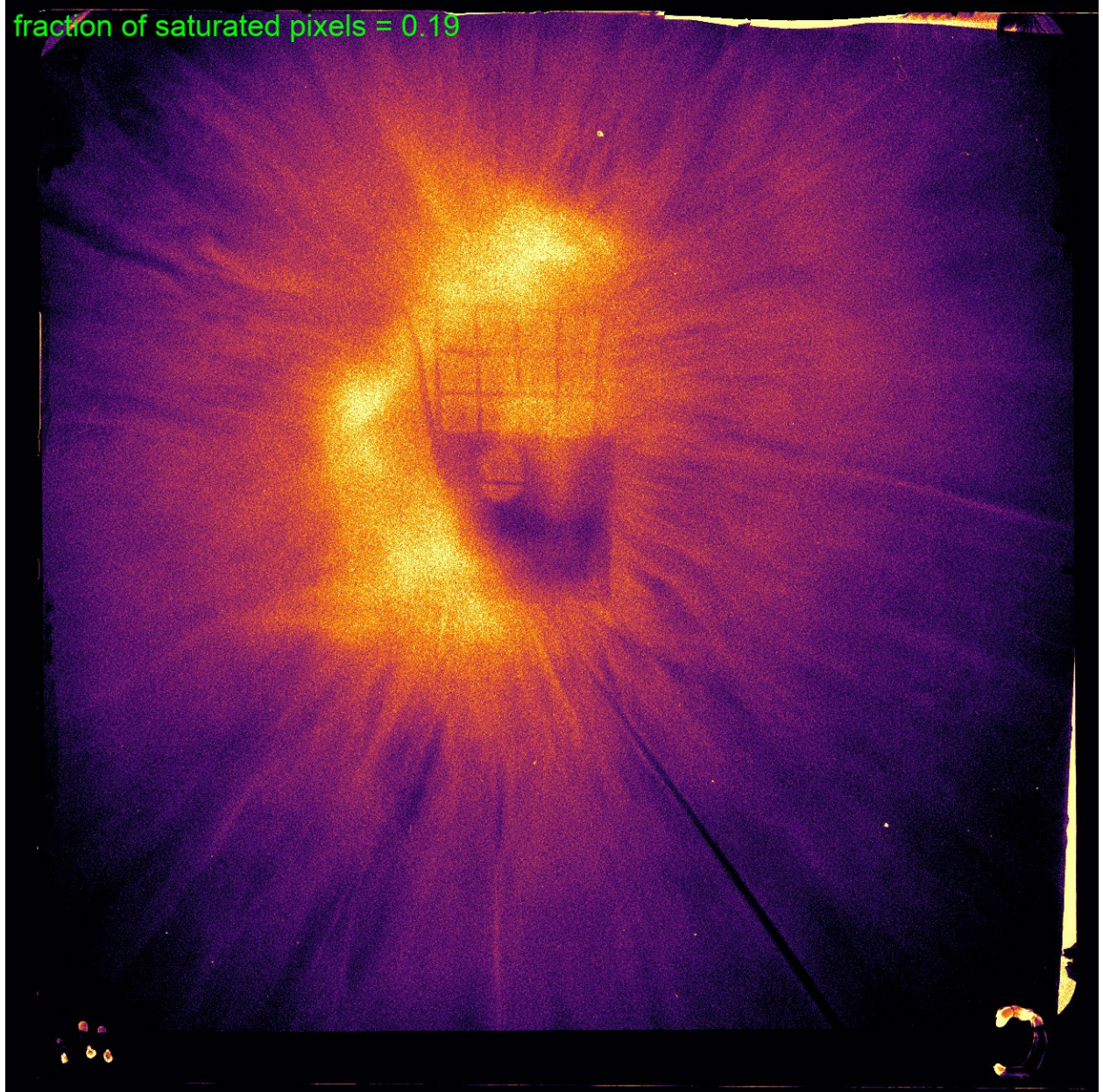


fraction of saturated pixels = 0.07



Shot 36437

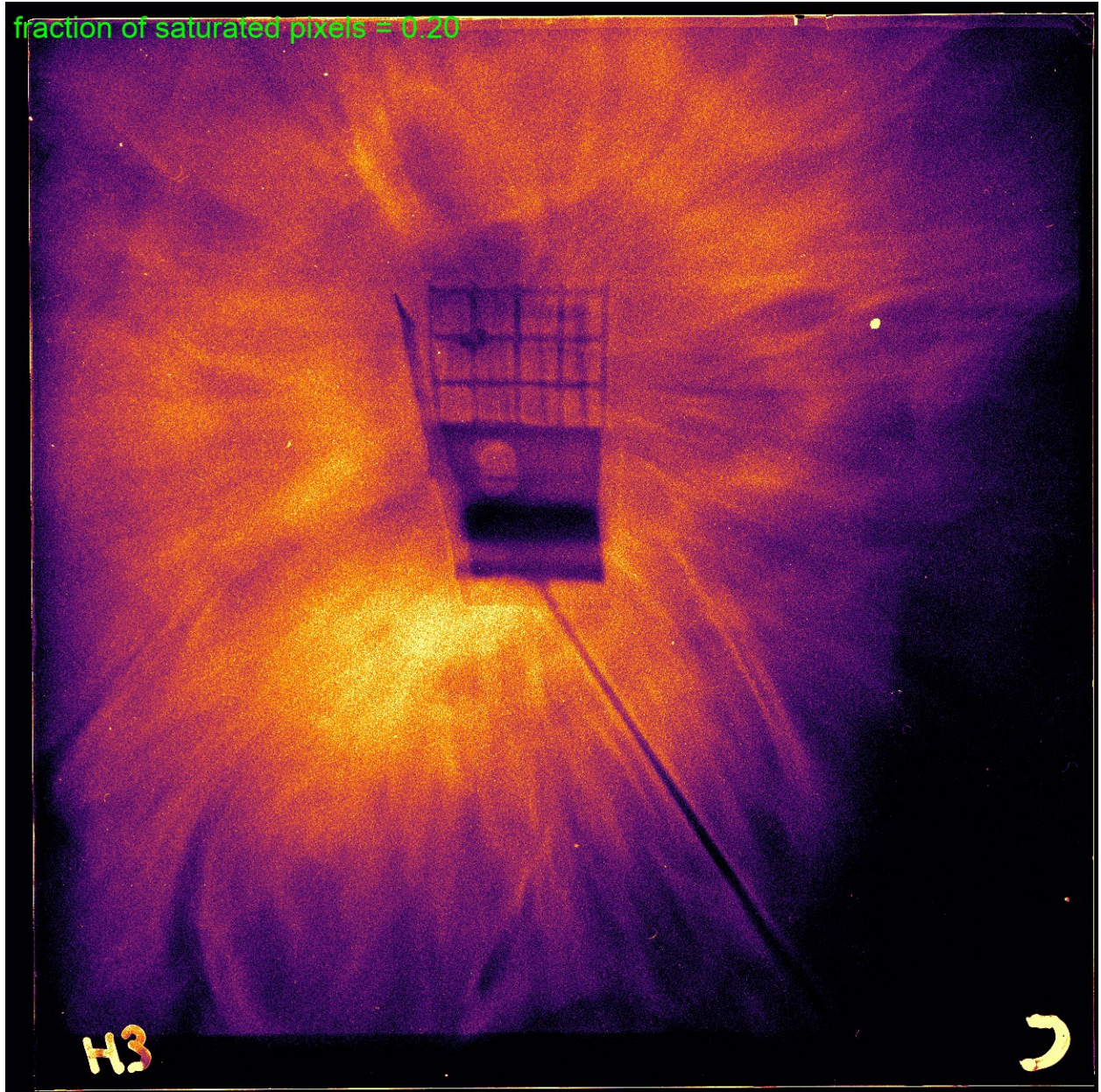
fraction of saturated pixels = 0.19



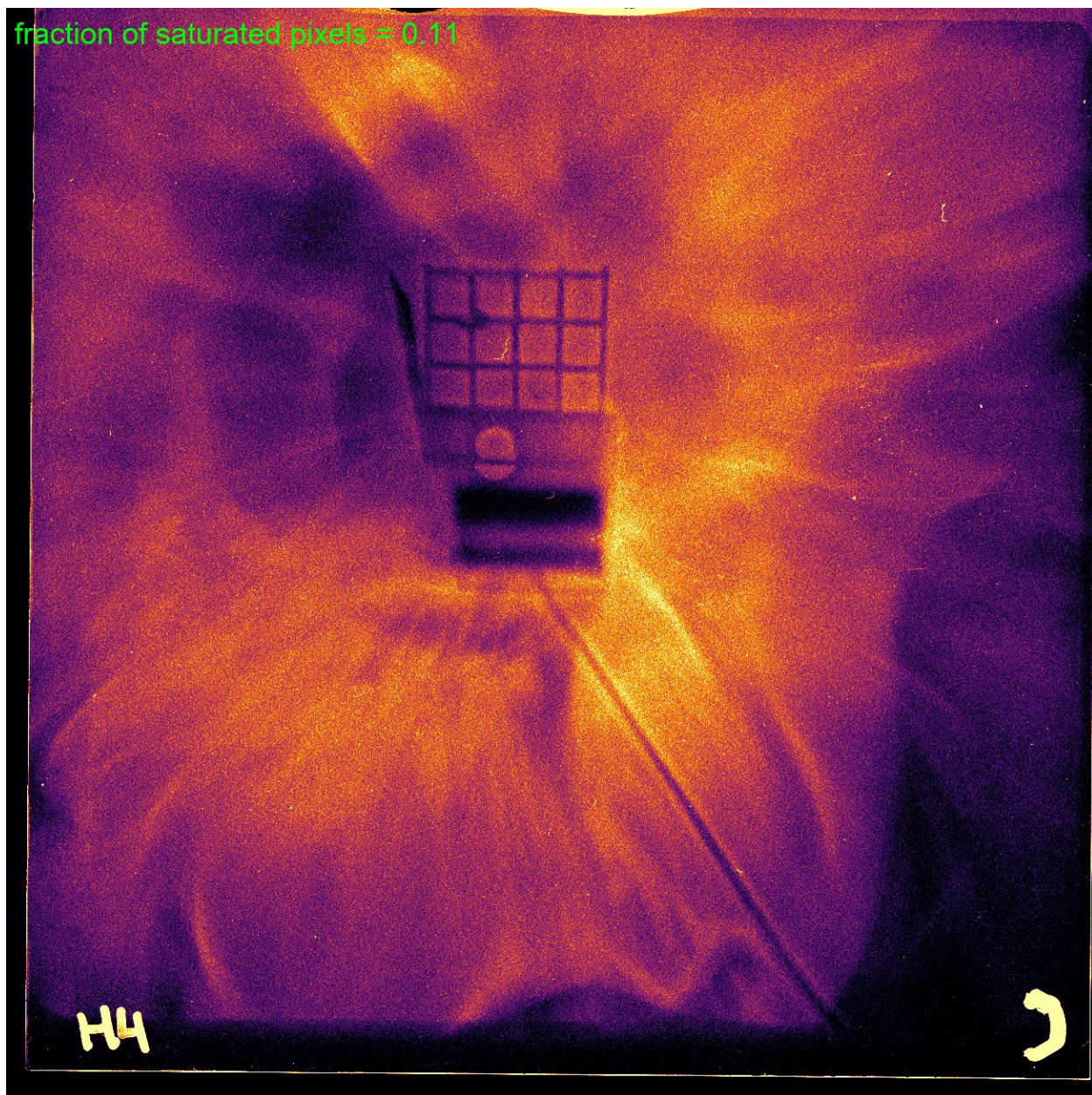
fraction of saturated pixels = 0.27



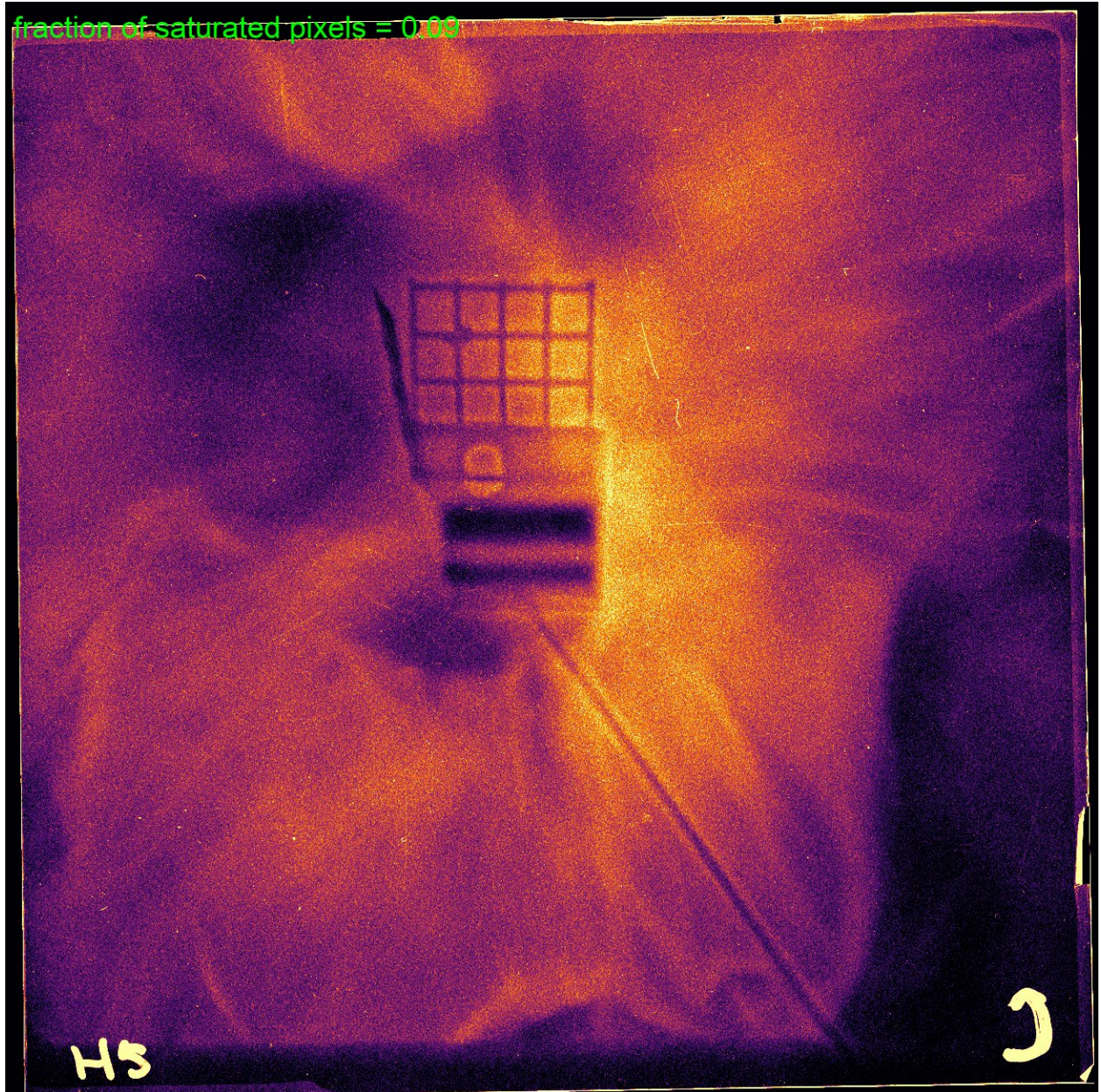
fraction of saturated pixels = 0.20



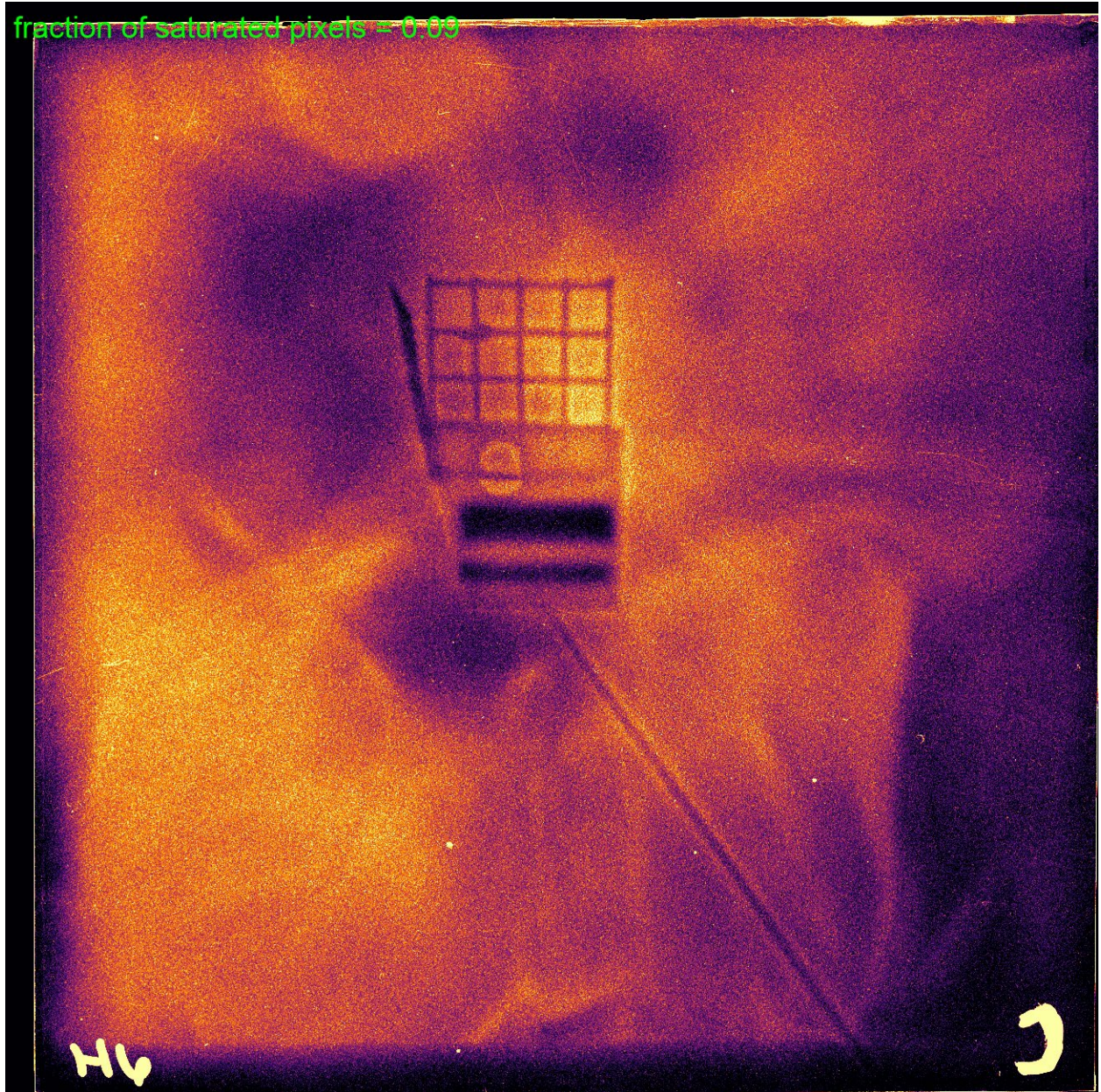
fraction of saturated pixels = 0.11



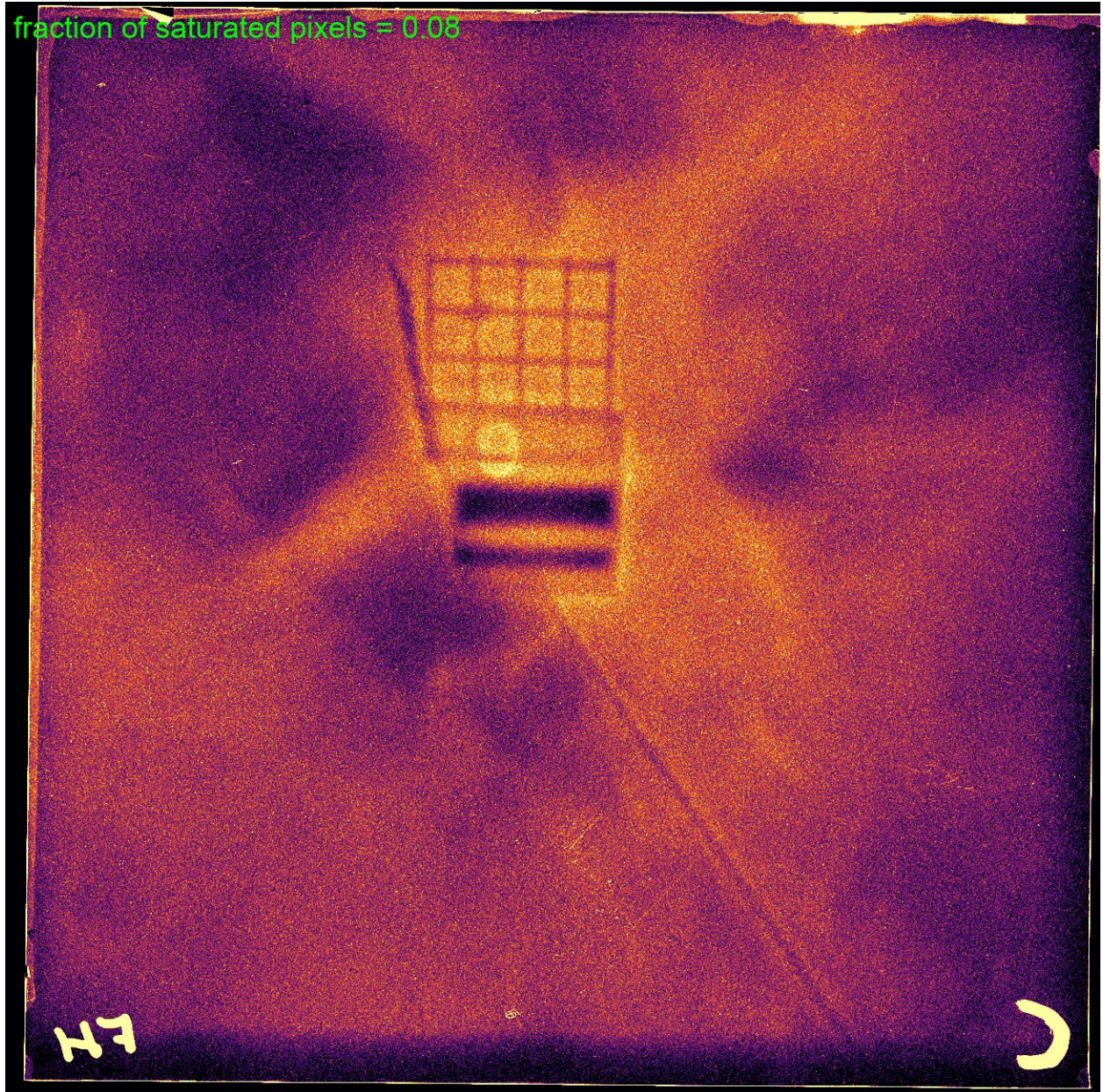
fraction of saturated pixels = 0.09



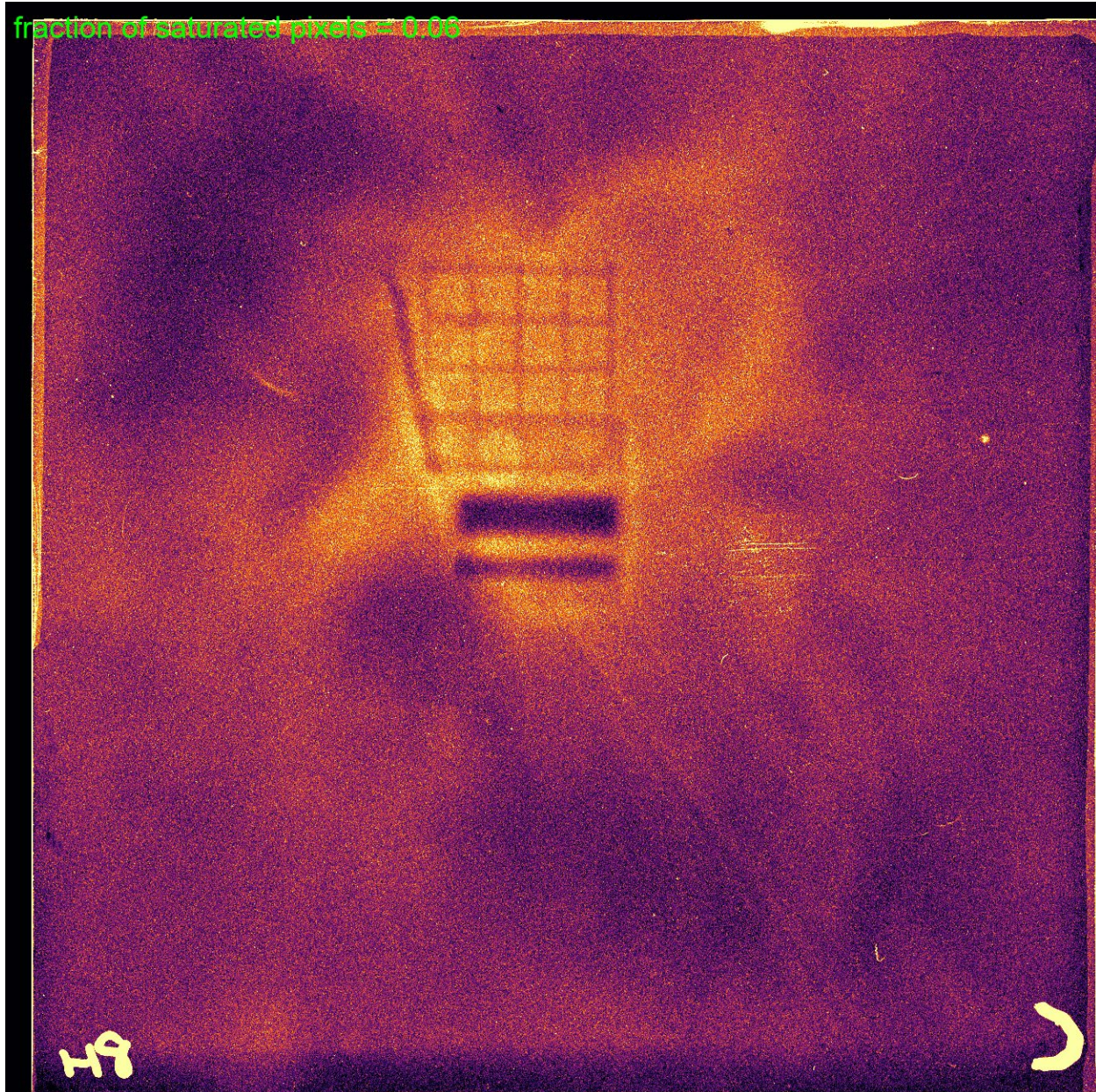
fraction of saturated pixels = 0.09



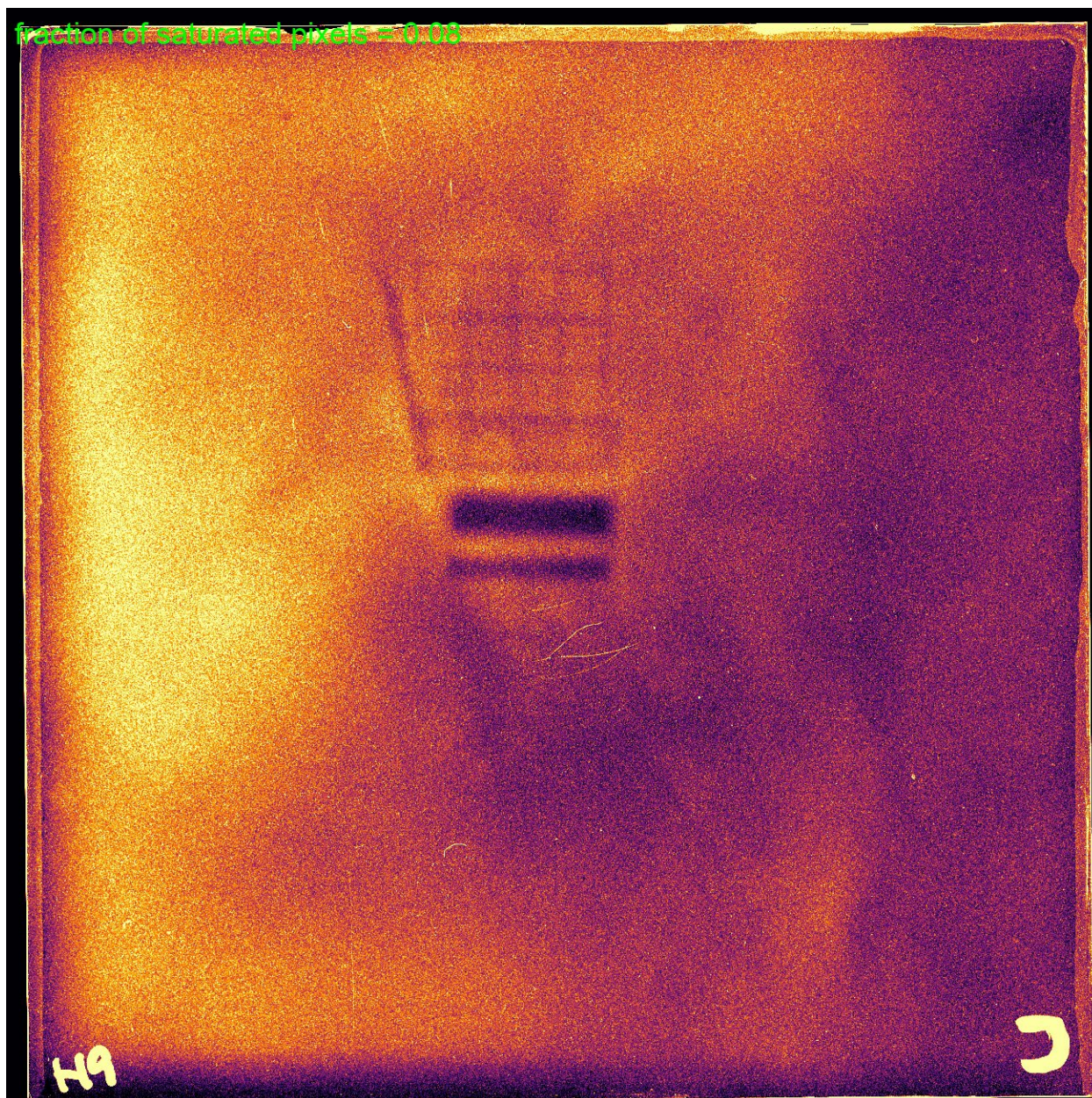
fraction of saturated pixels = 0.08



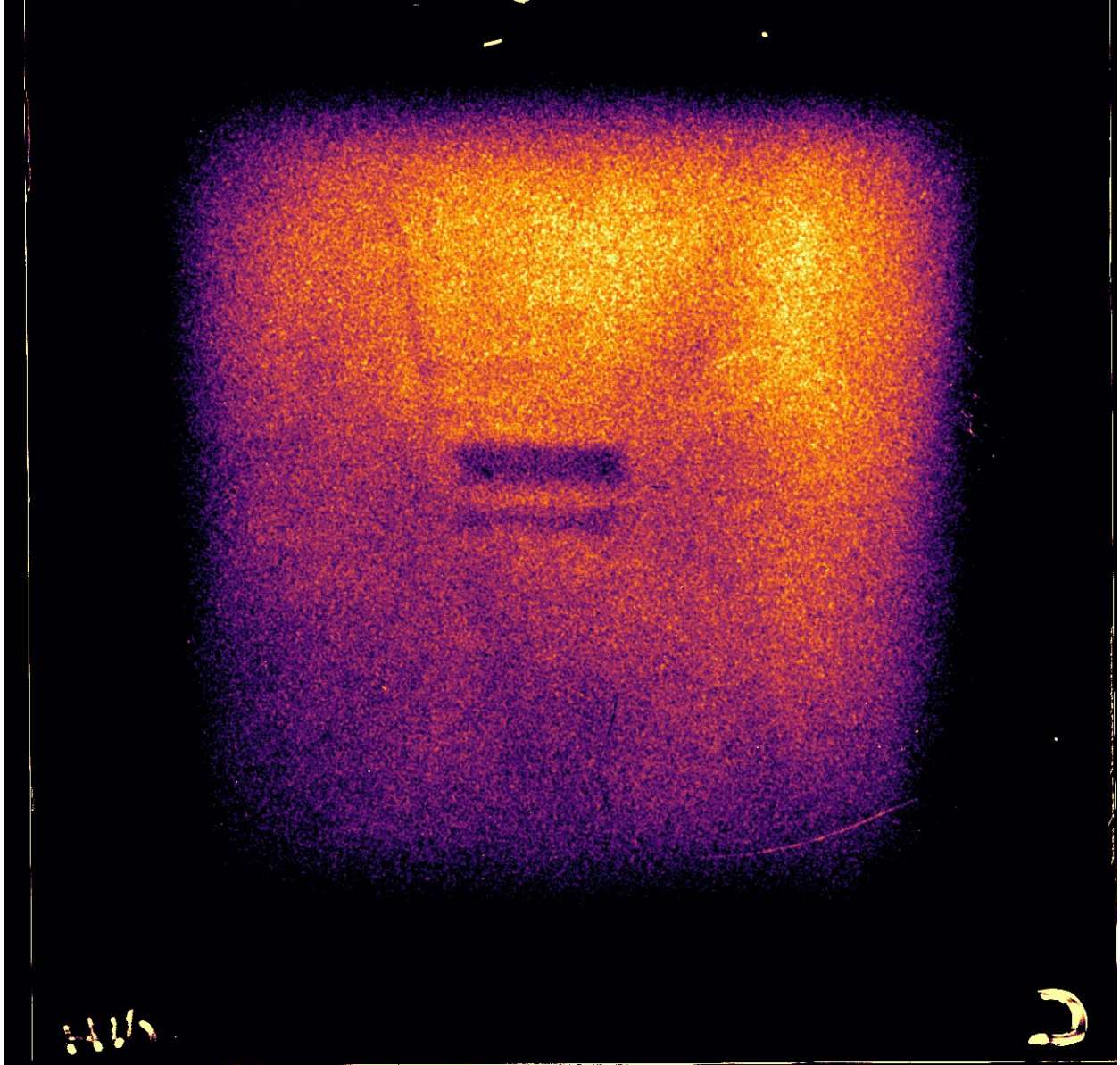
fraction of saturated pixels = 0.05



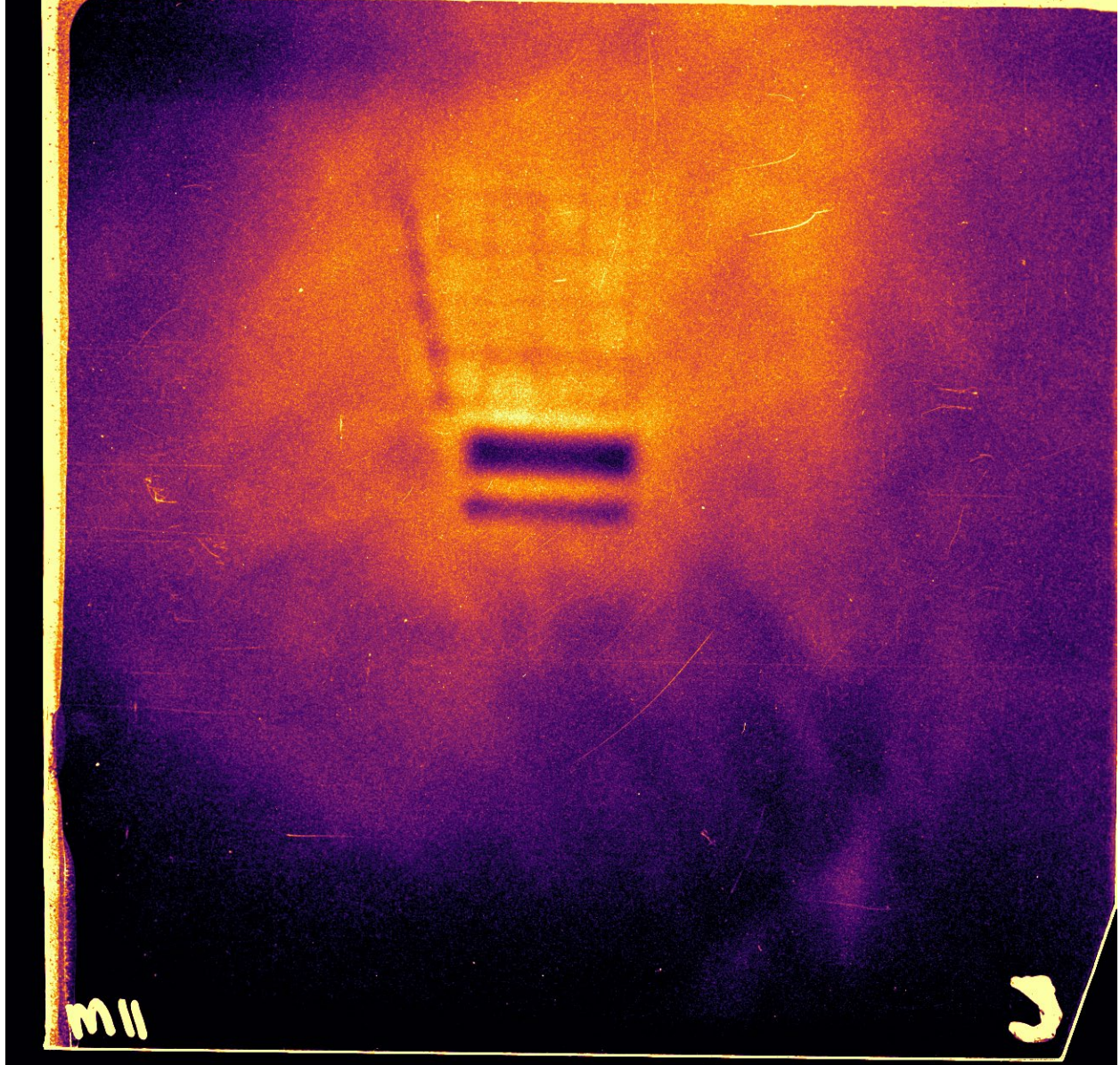
fraction of saturated pixels = 0.03



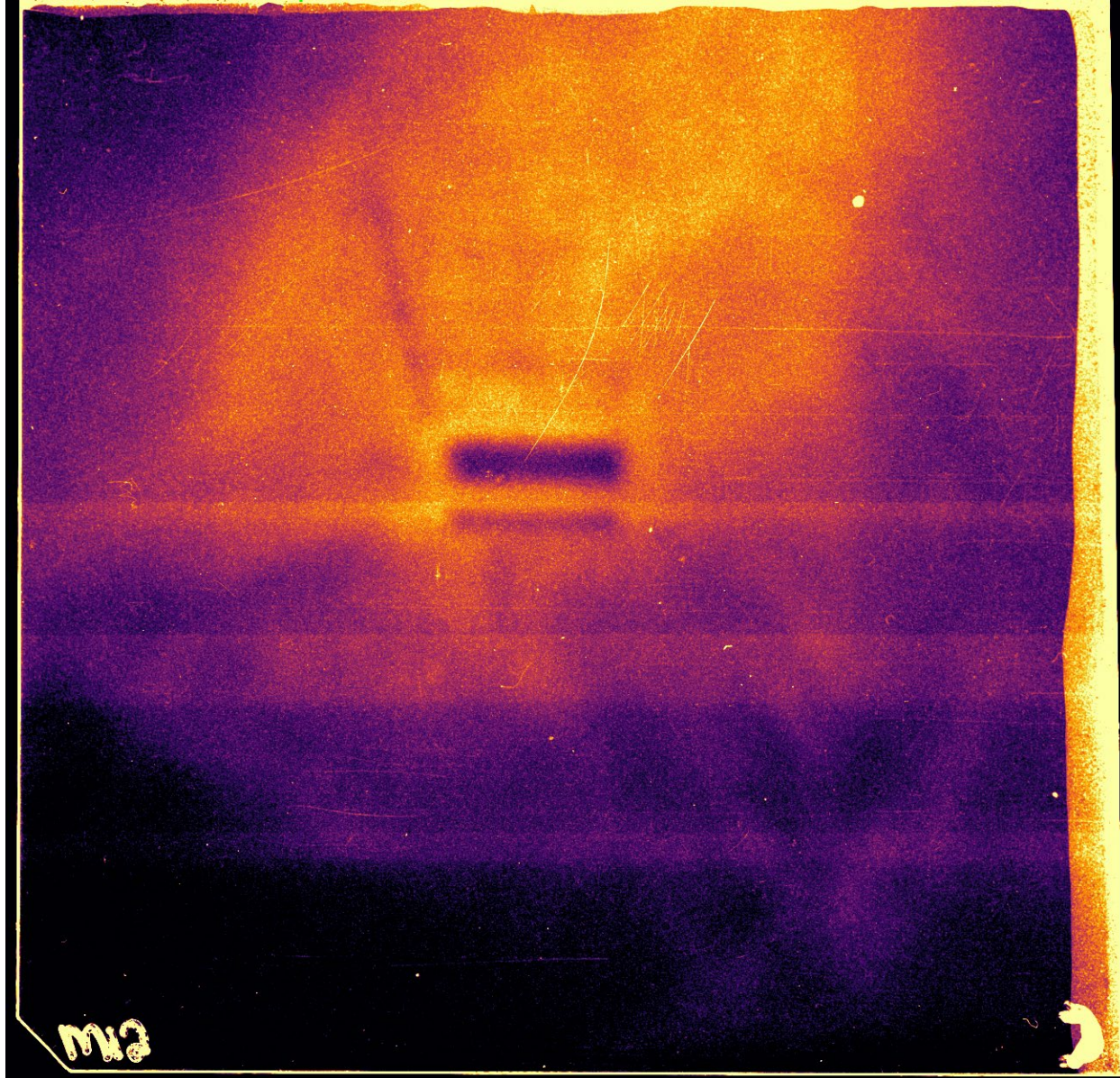
fraction of saturated pixels = 0.53



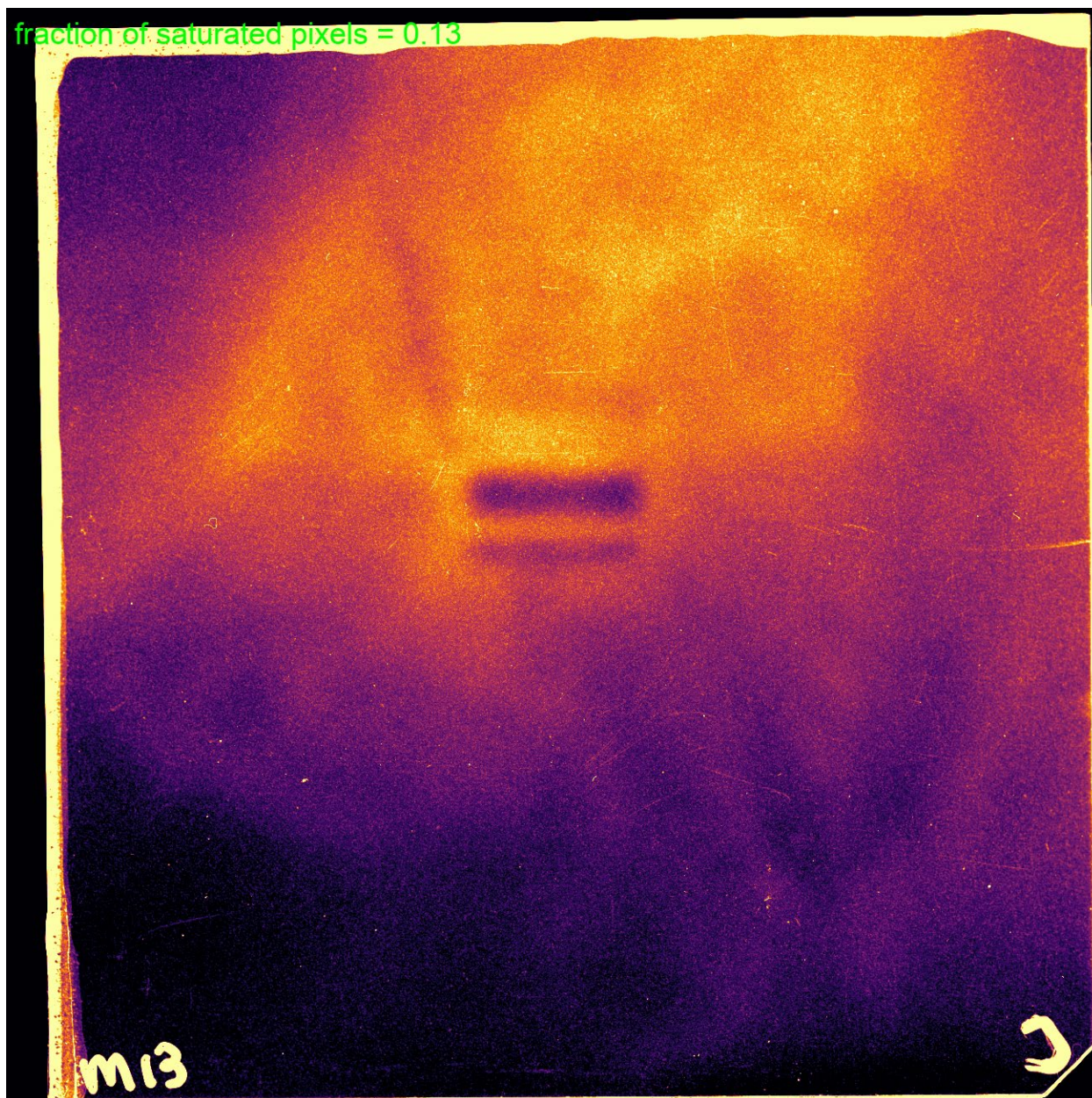
fraction of saturated pixels = 0.19

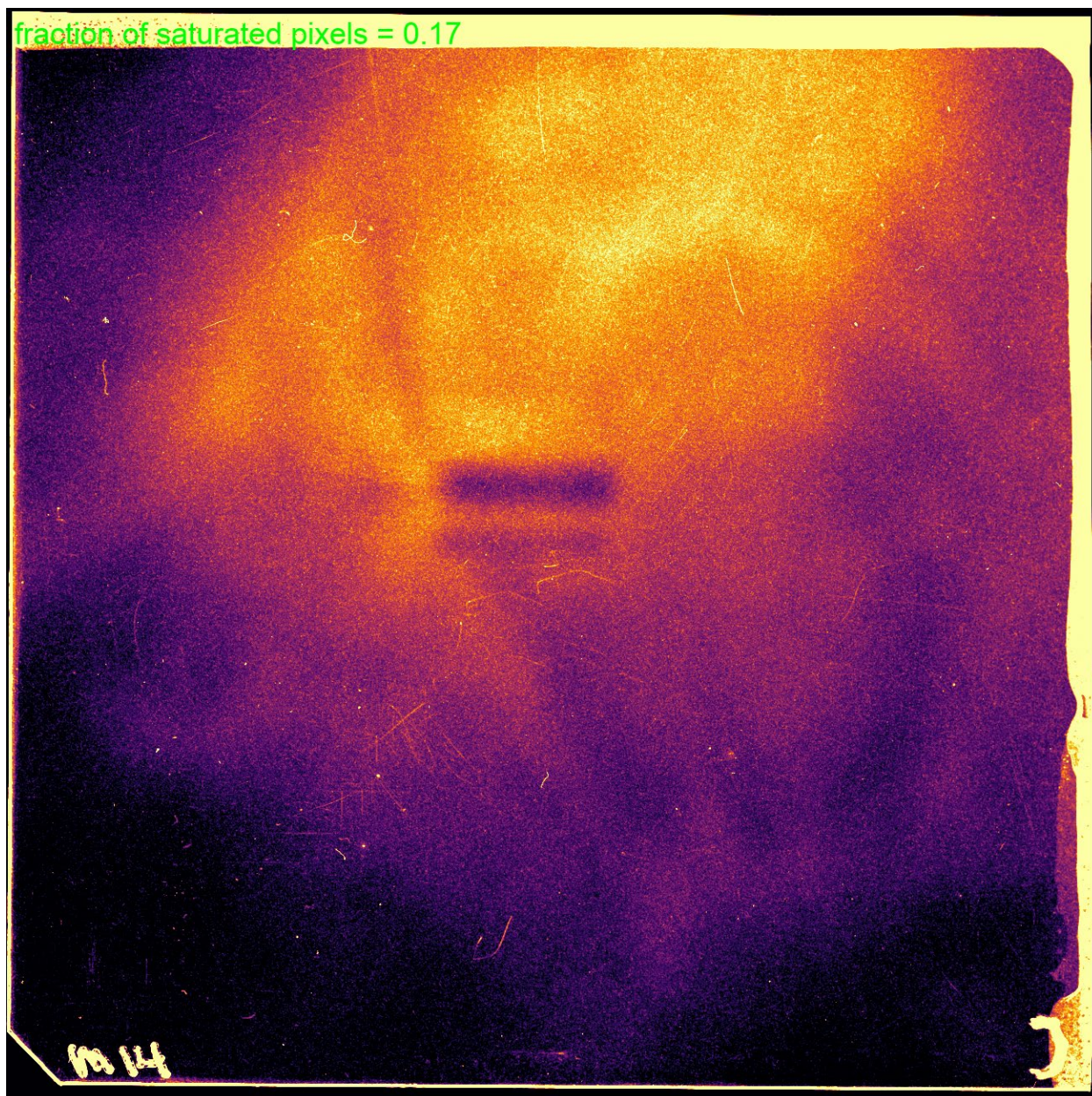


fraction of saturated pixels = 0.20



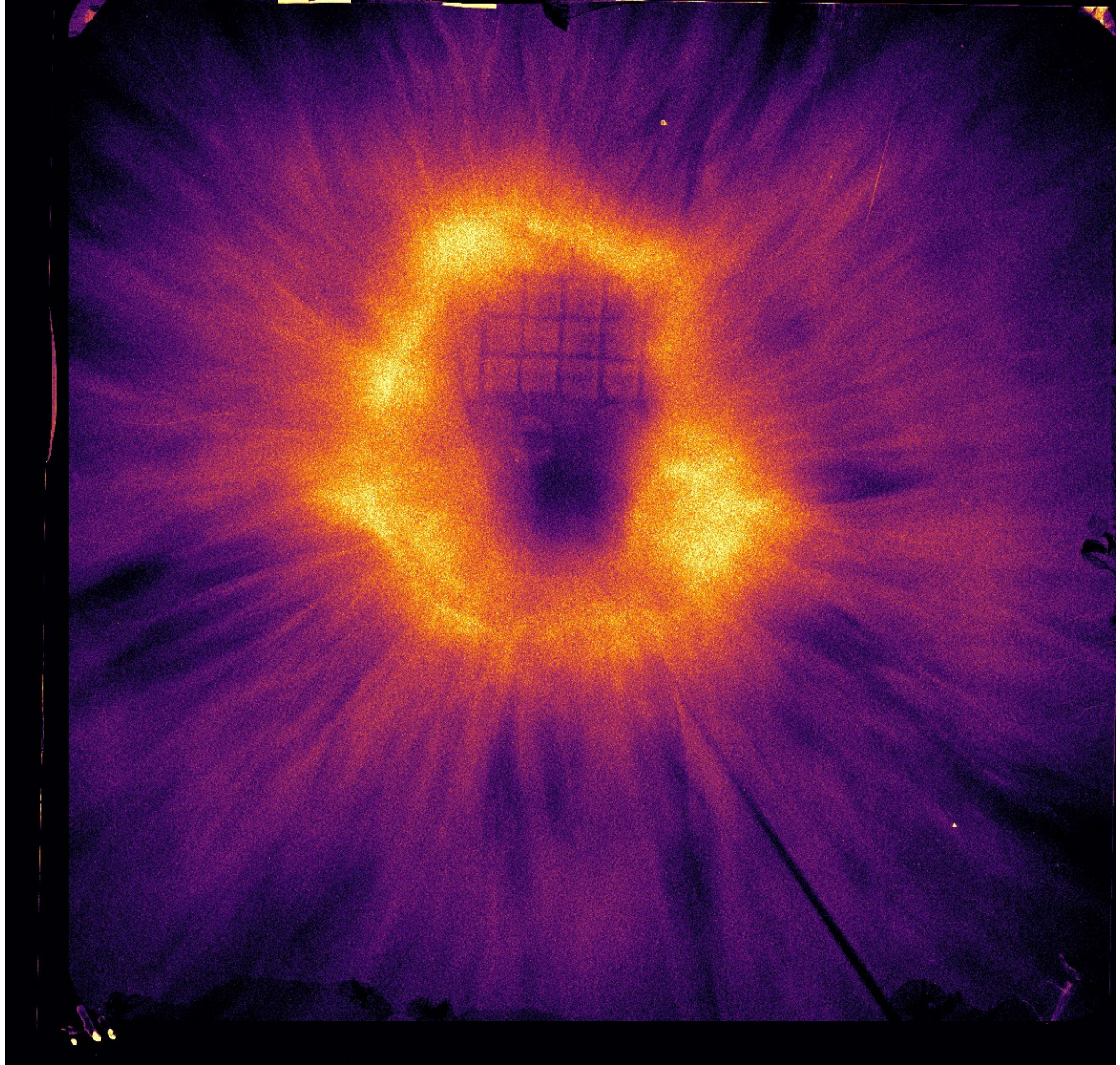
fraction of saturated pixels = 0.13



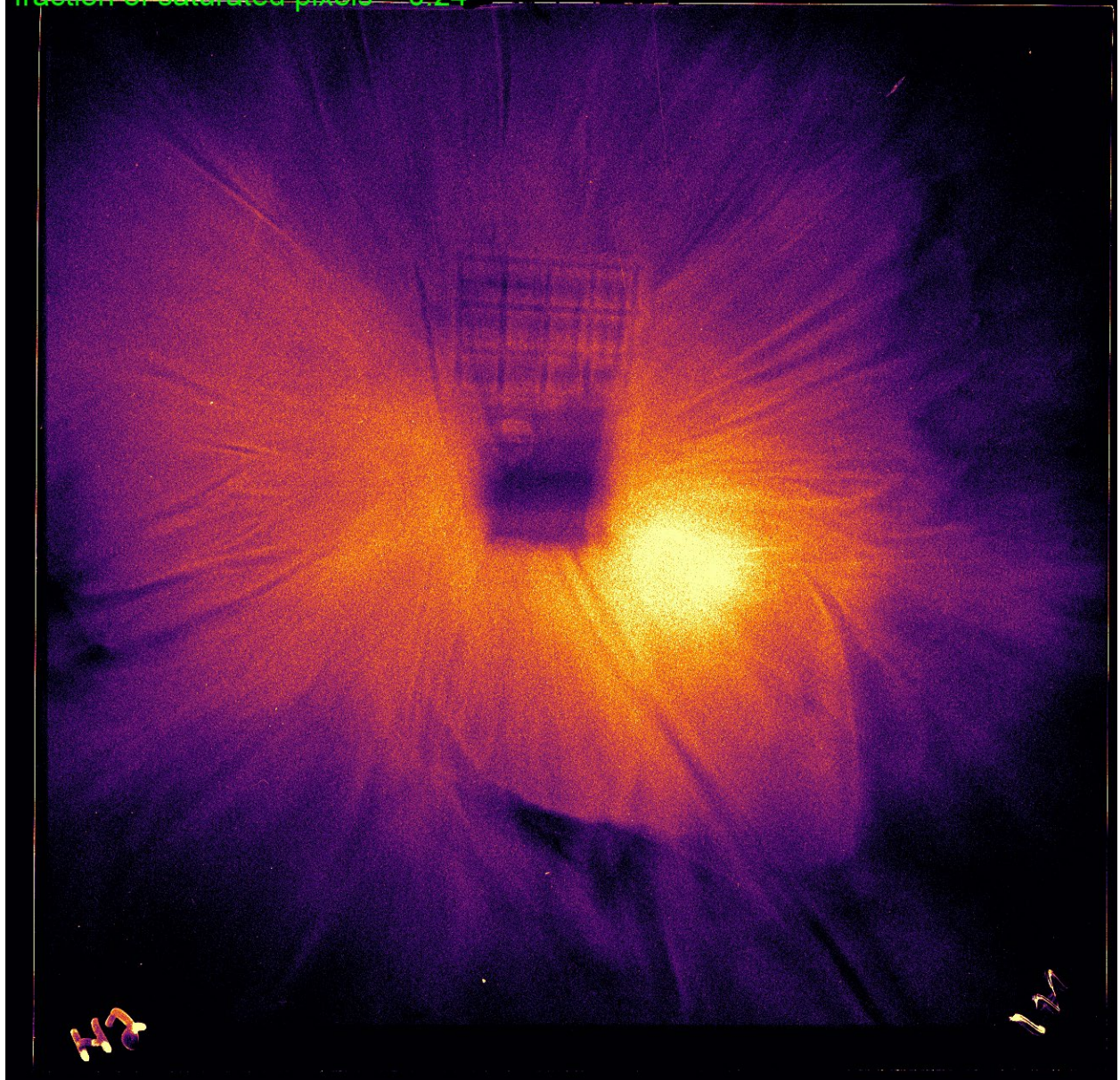


Shot 36438

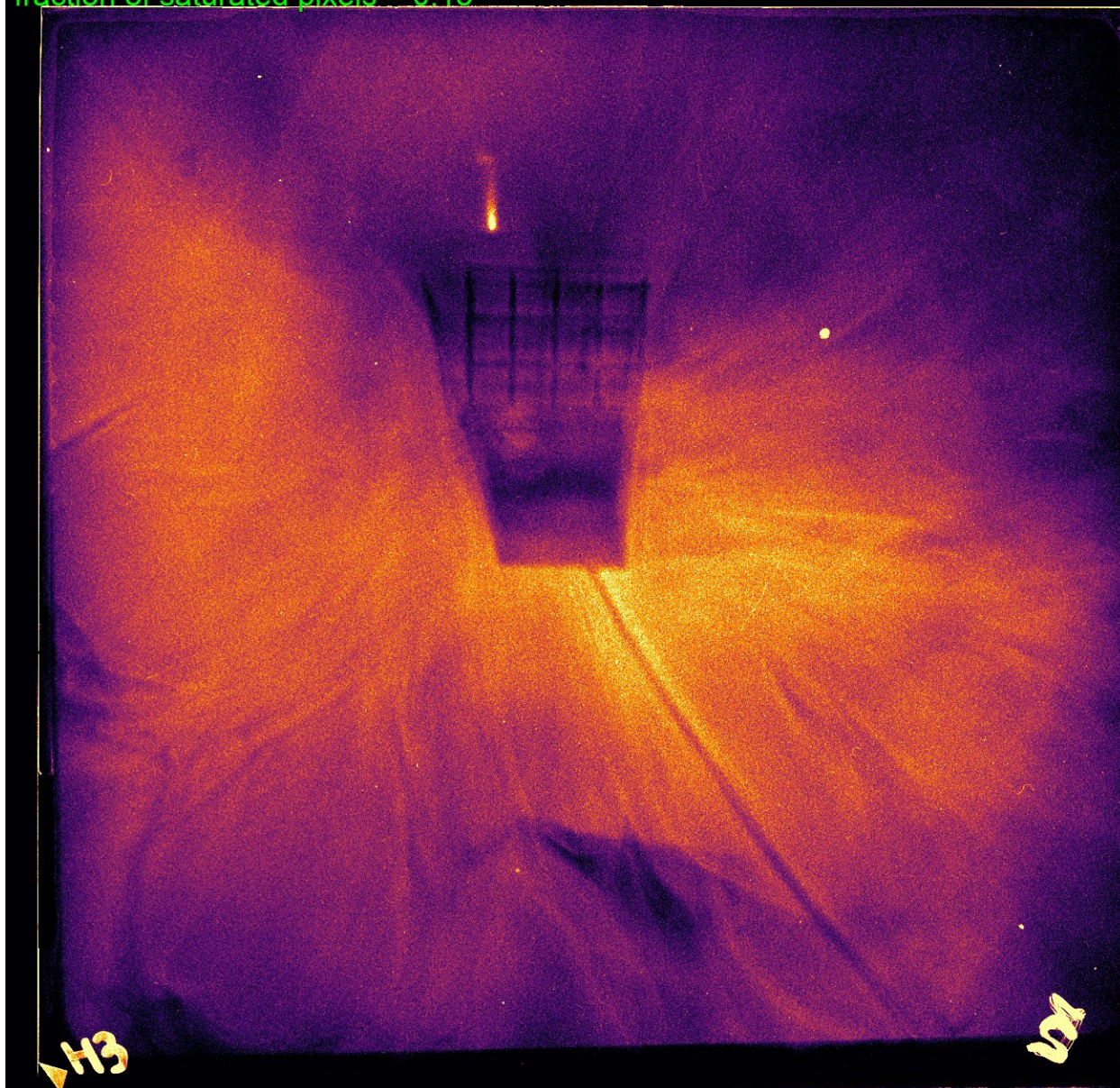
fraction of saturated pixels = 0.17



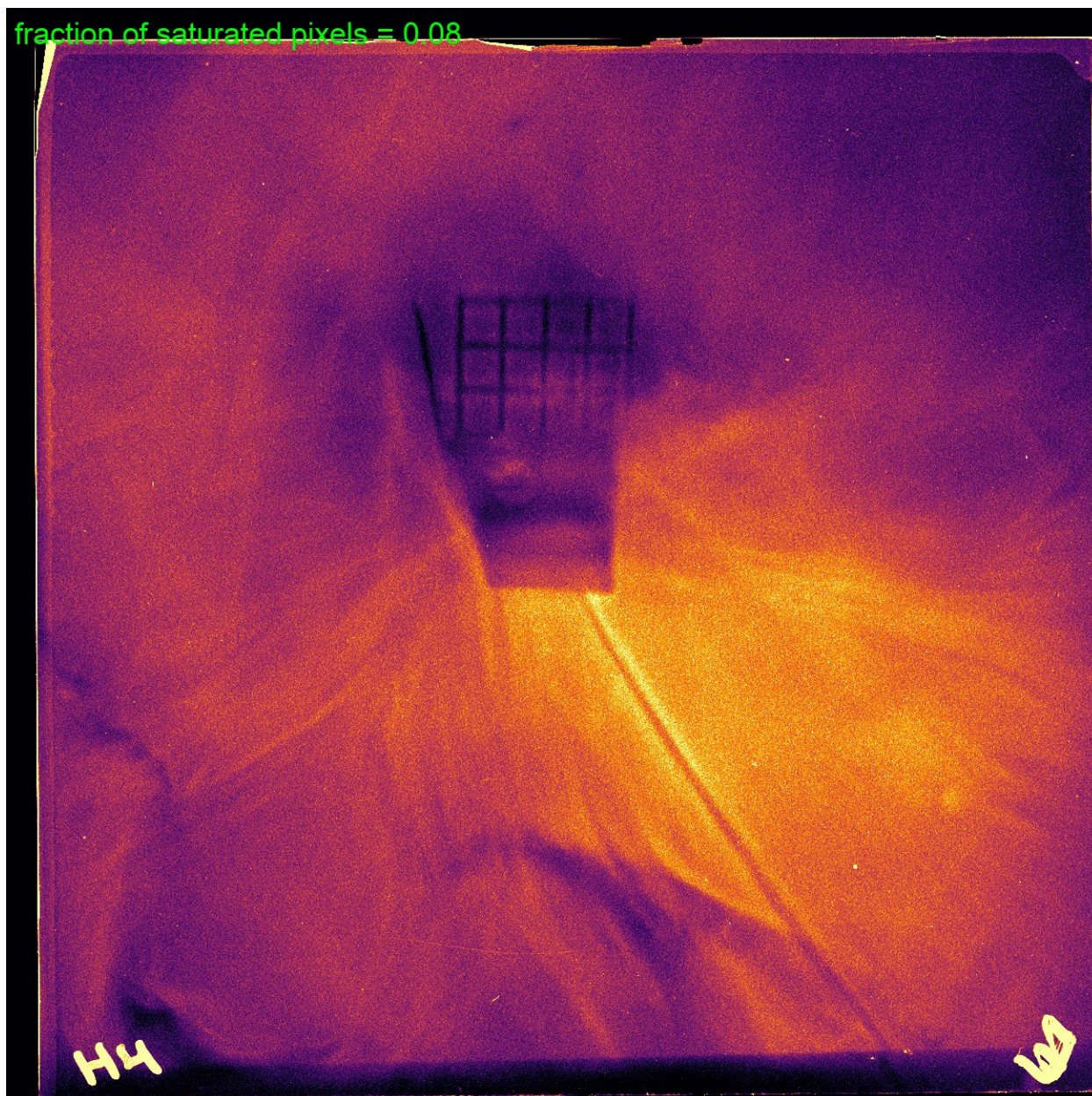
fraction of saturated pixels = 0.24



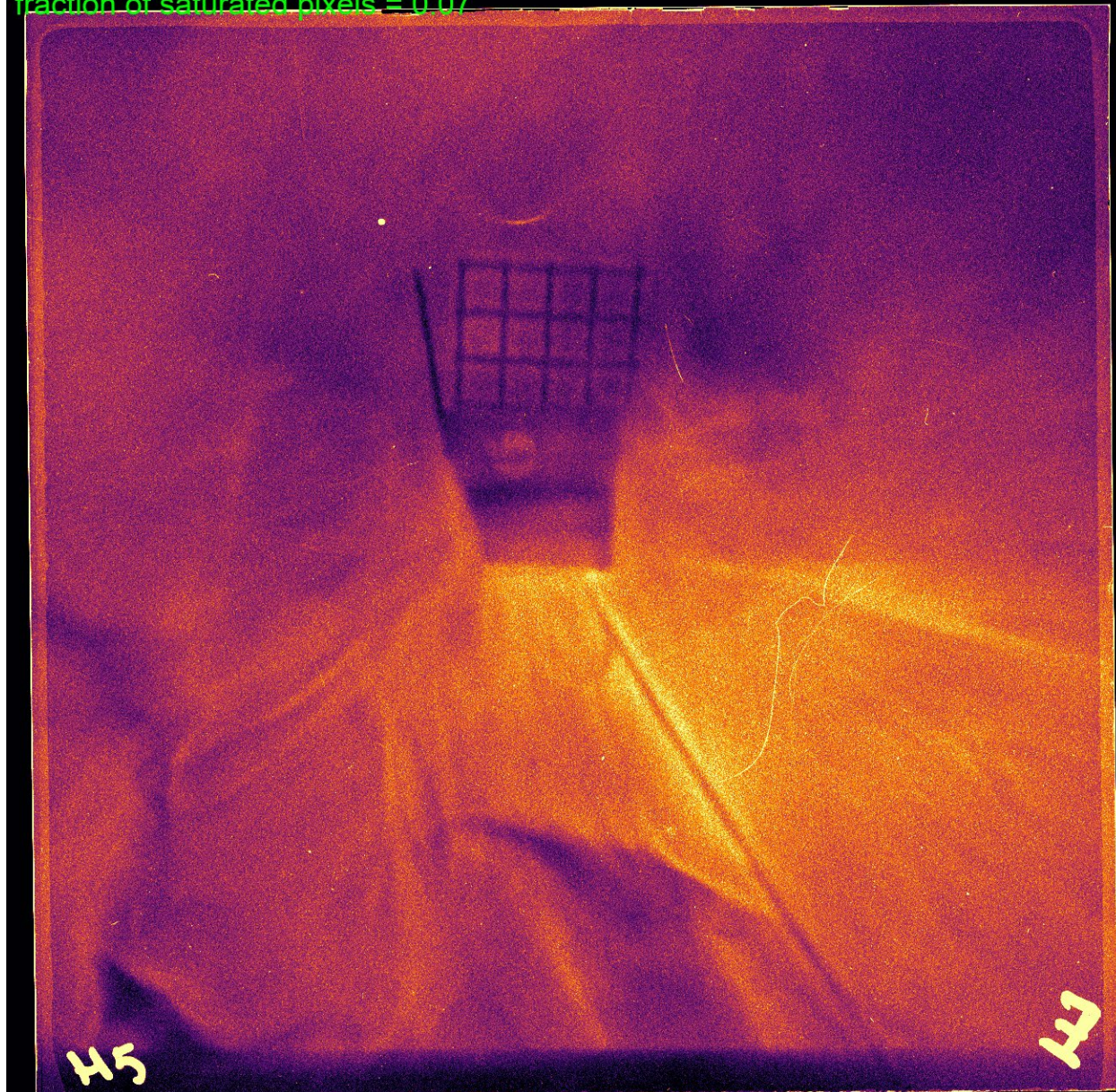
fraction of saturated pixels = 0.13



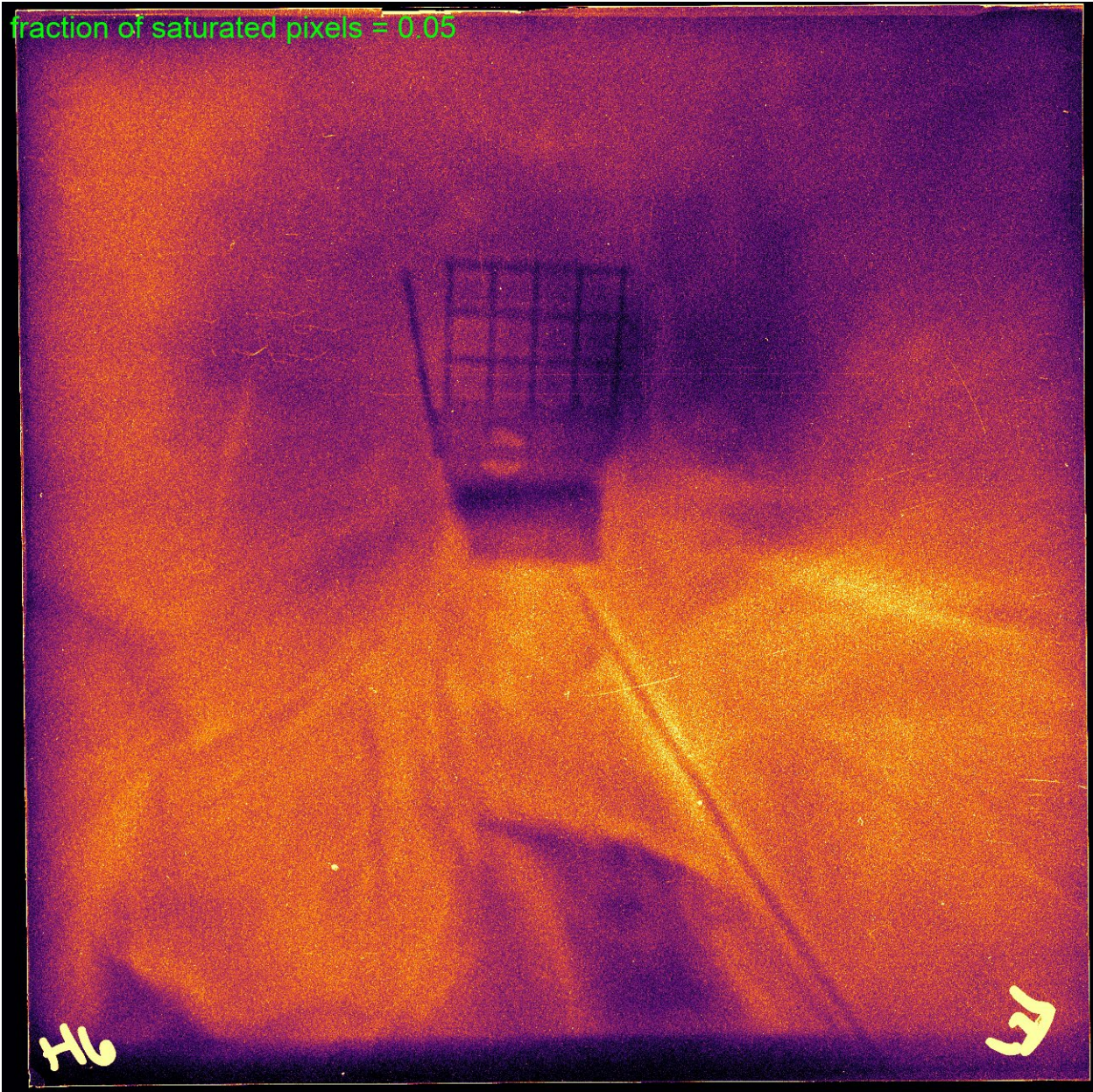
fraction of saturated pixels = 0.08



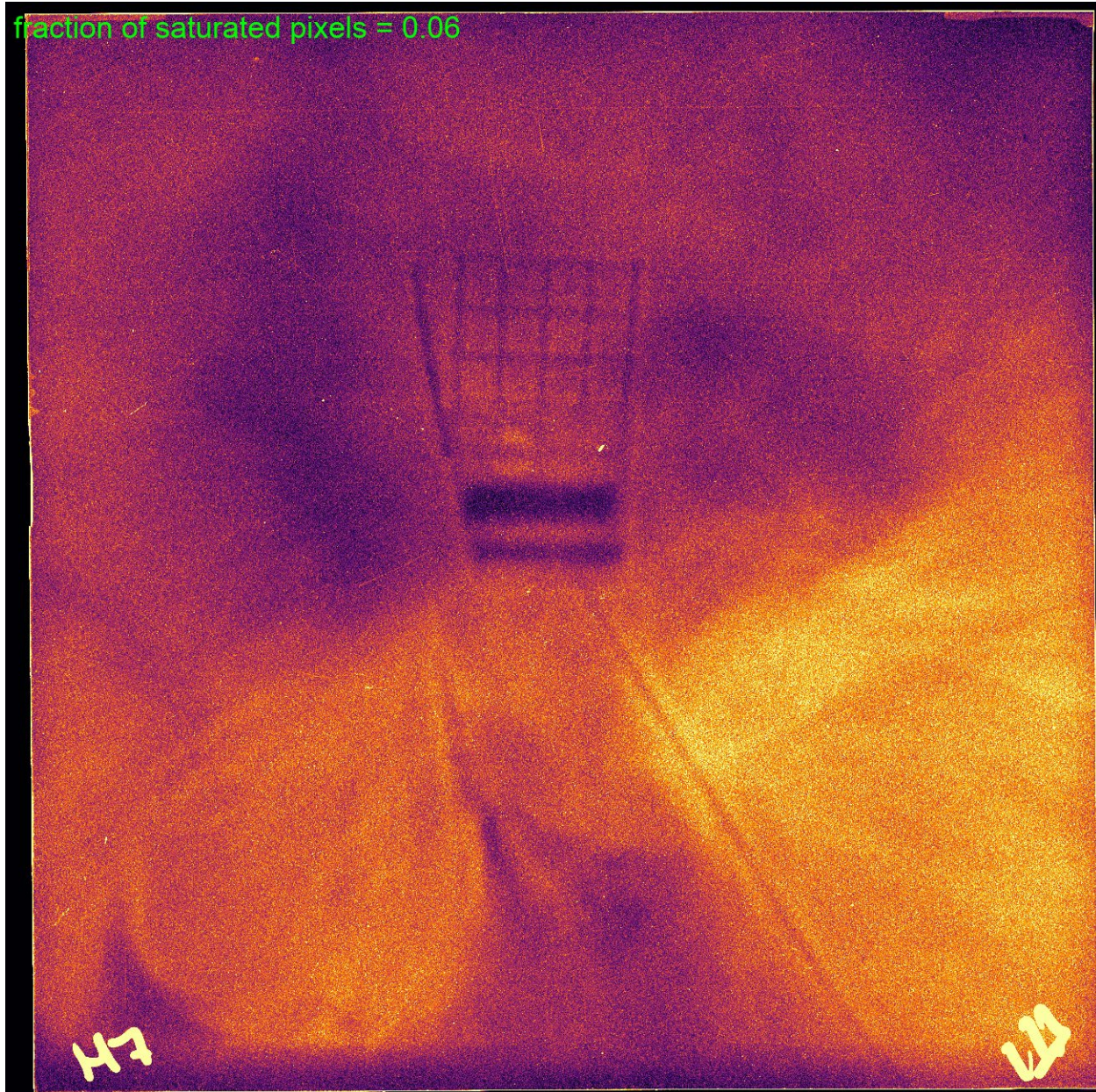
fraction of saturated pixels = 0.07



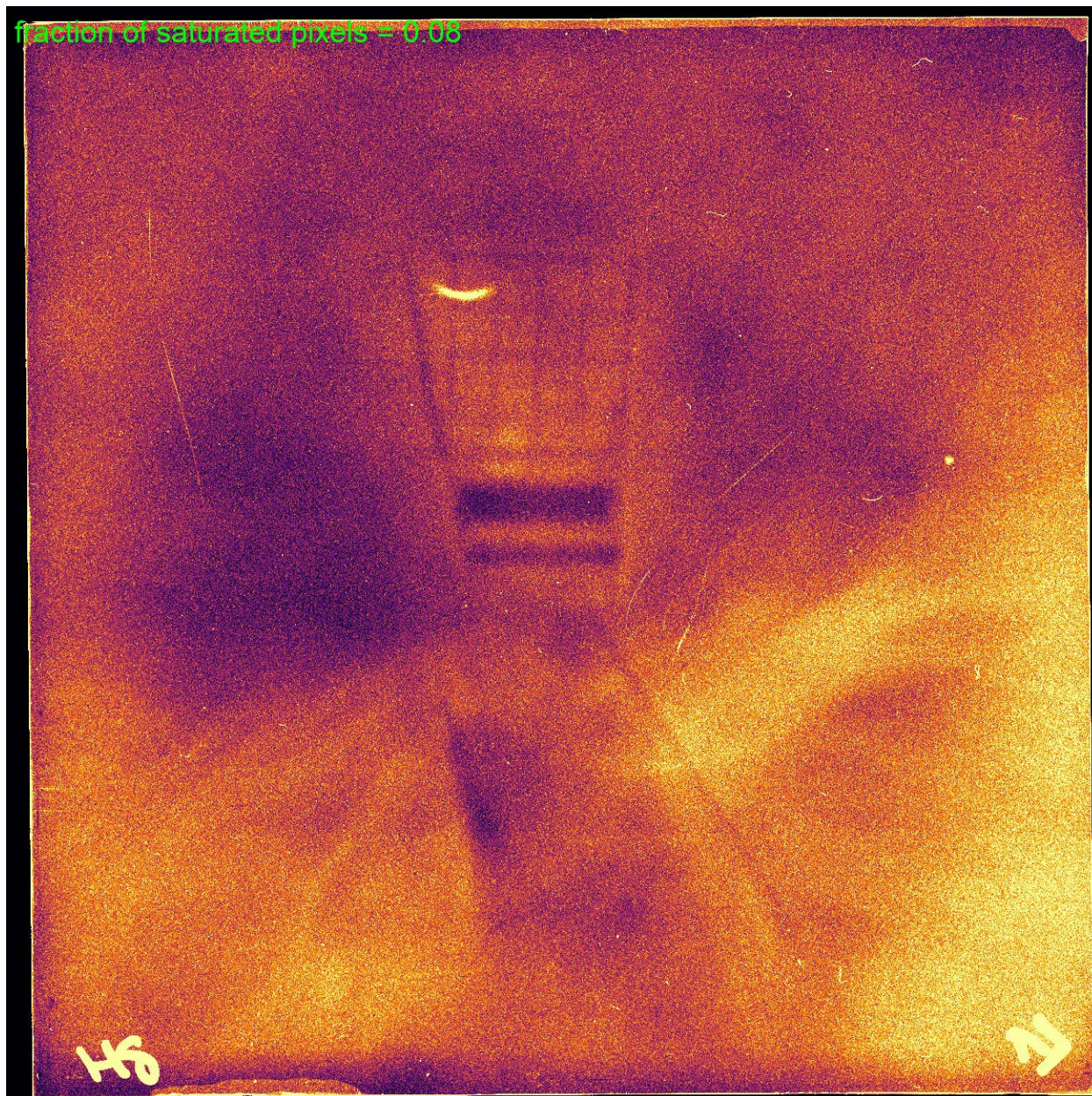
fraction of saturated pixels = 0.05



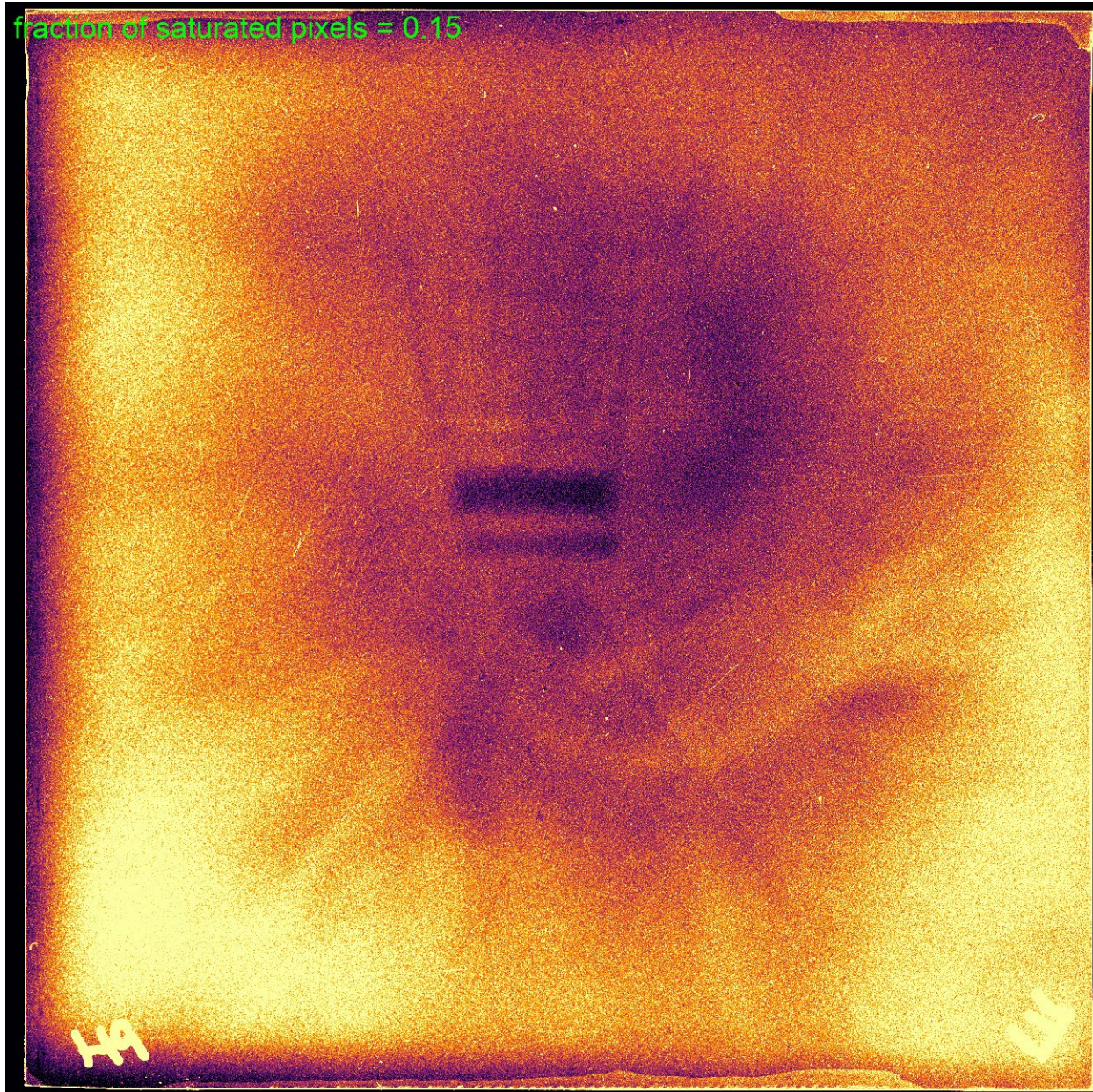
fraction of saturated pixels = 0.06

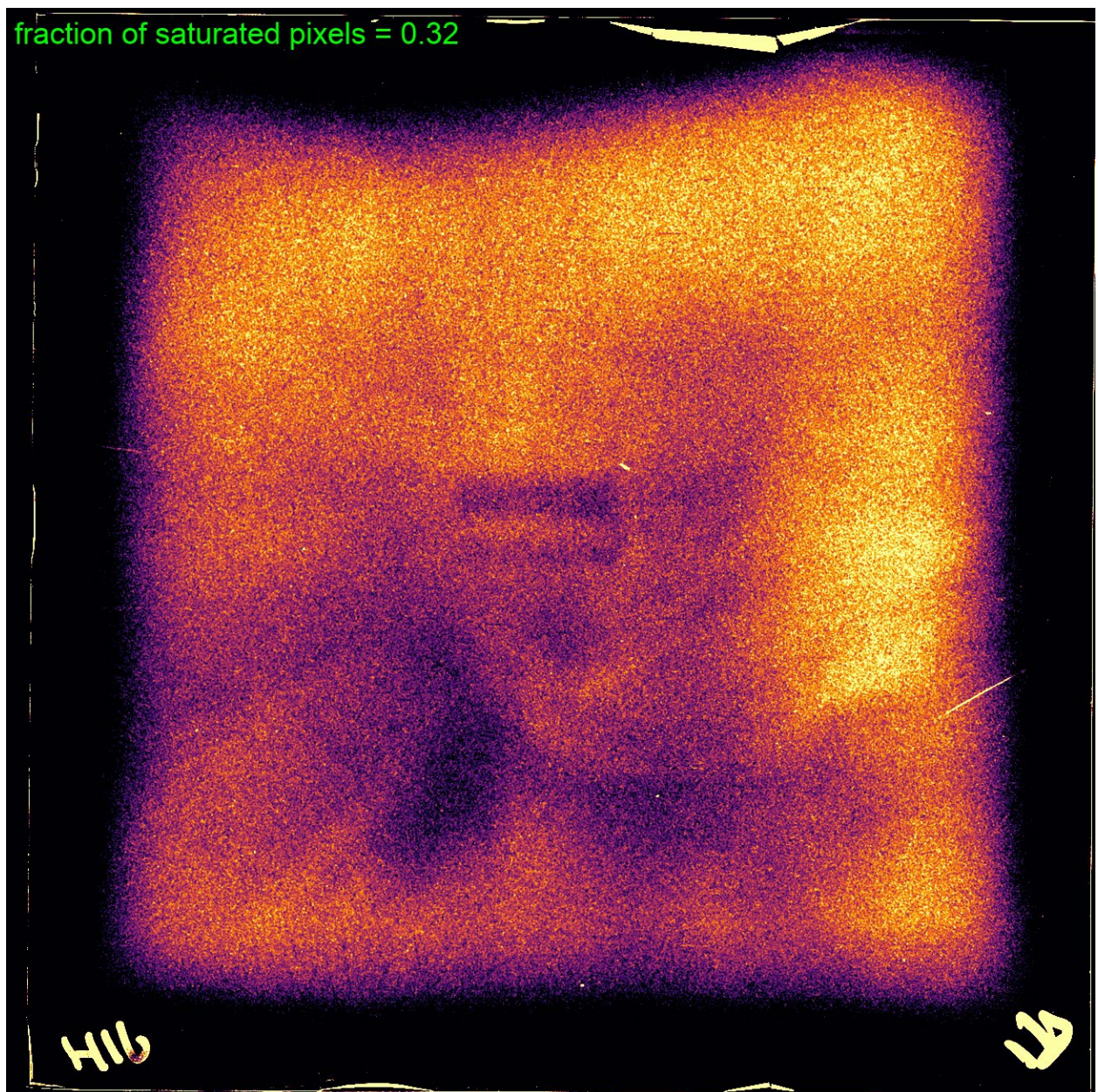


fraction of saturated pixels = 0.08

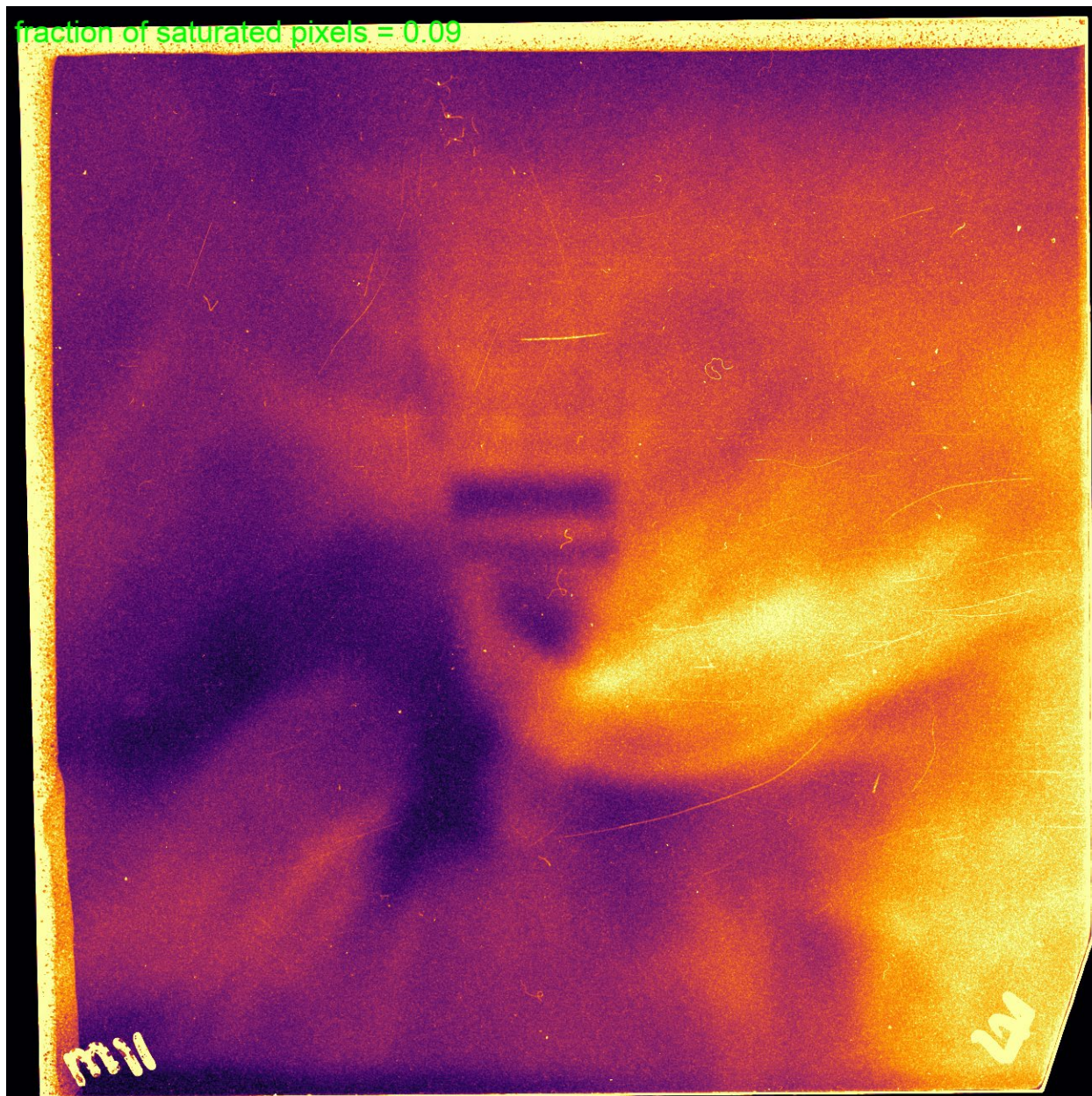


fraction of saturated pixels = 0.15

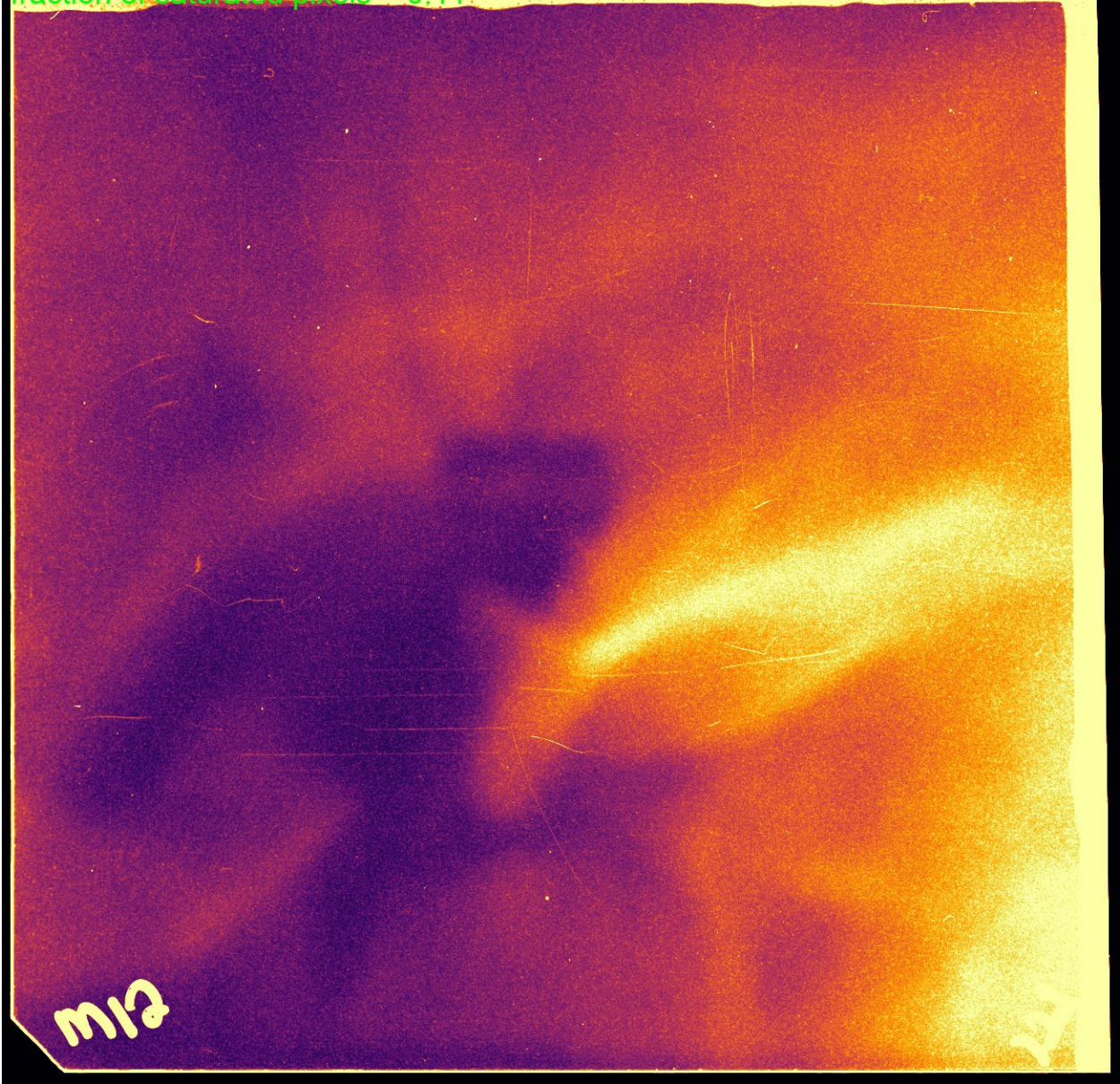




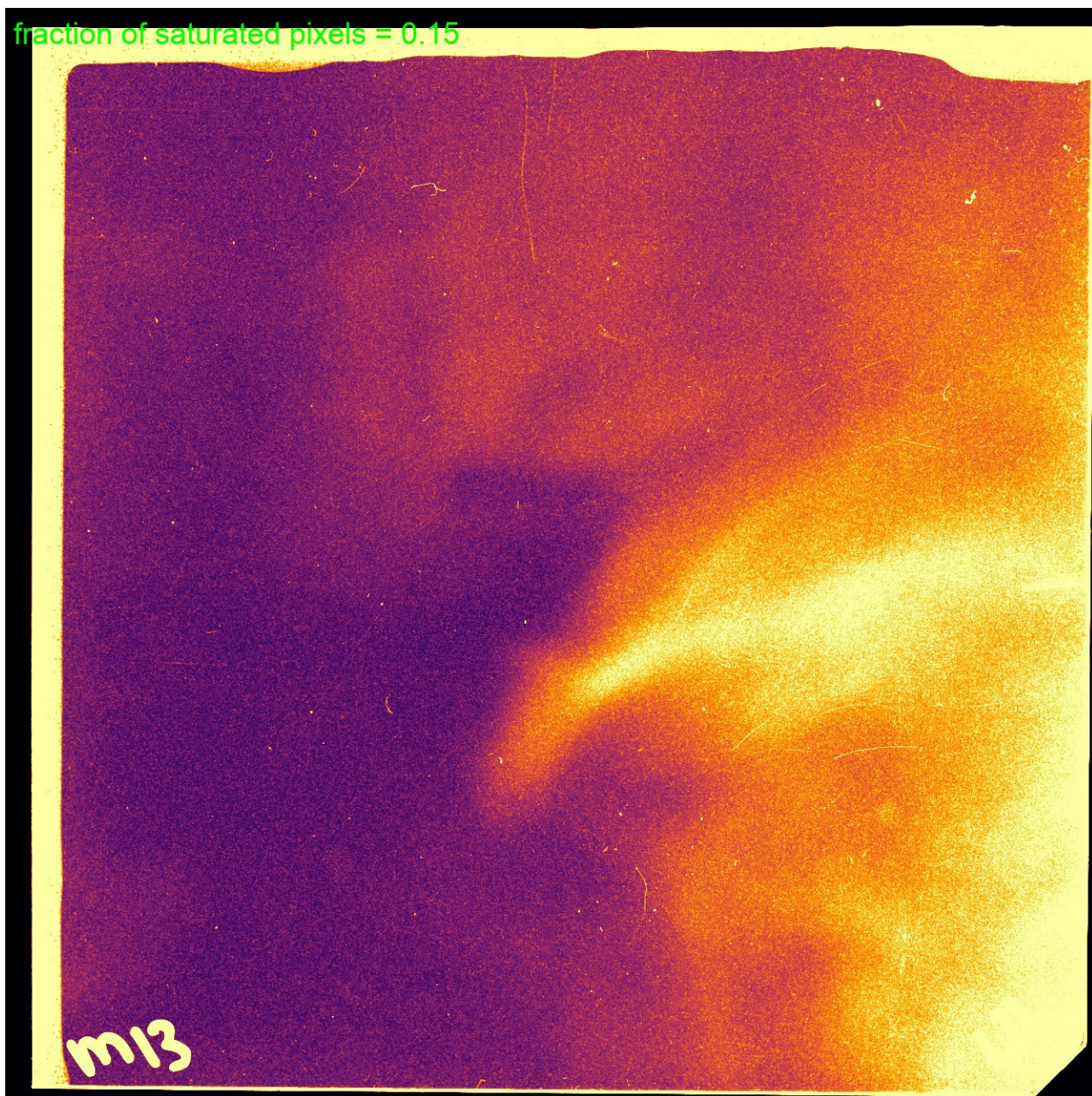
fraction of saturated pixels = 0.09



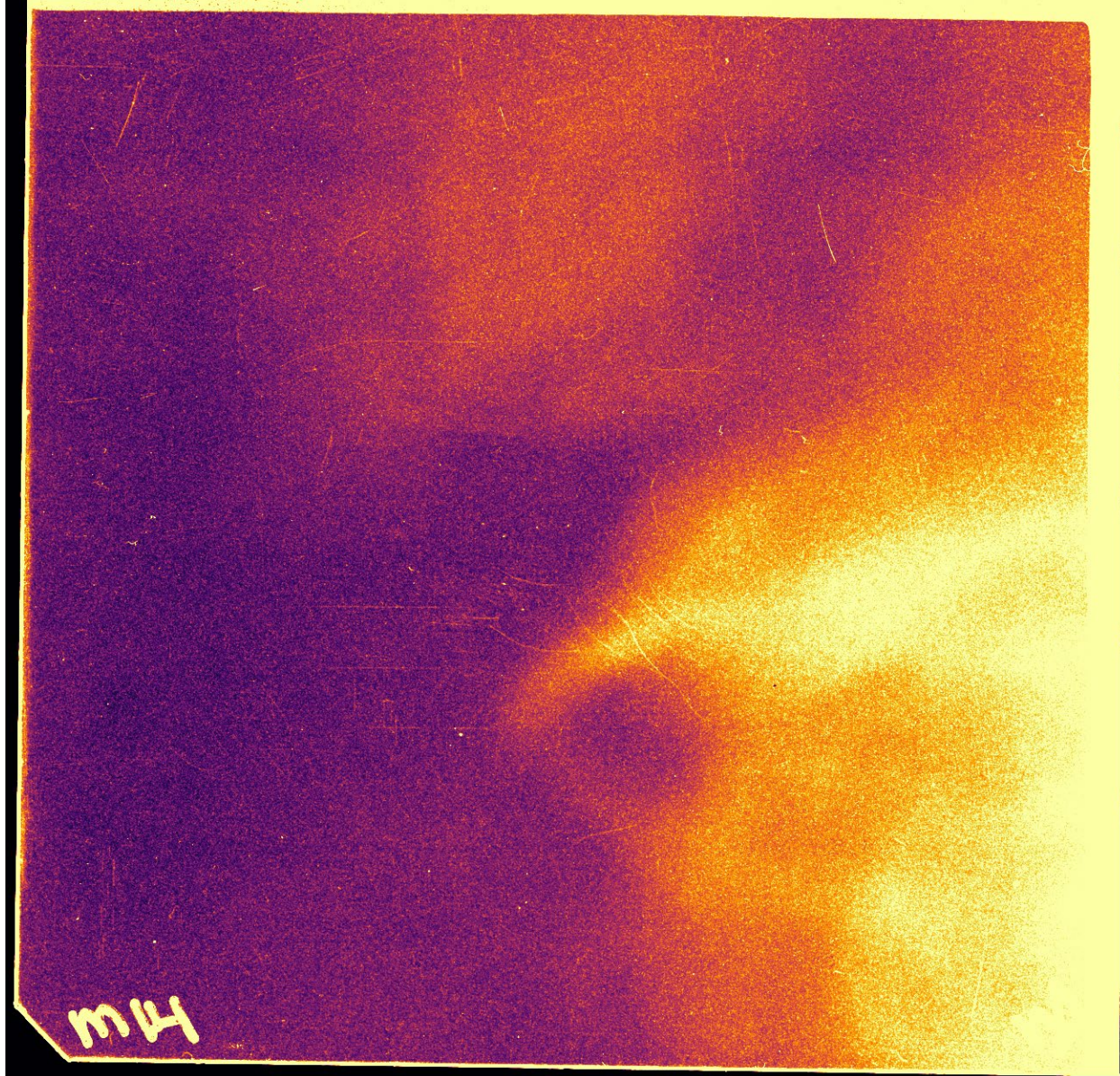
fraction of saturated pixels = 0.11



fraction of saturated pixels = 0.15

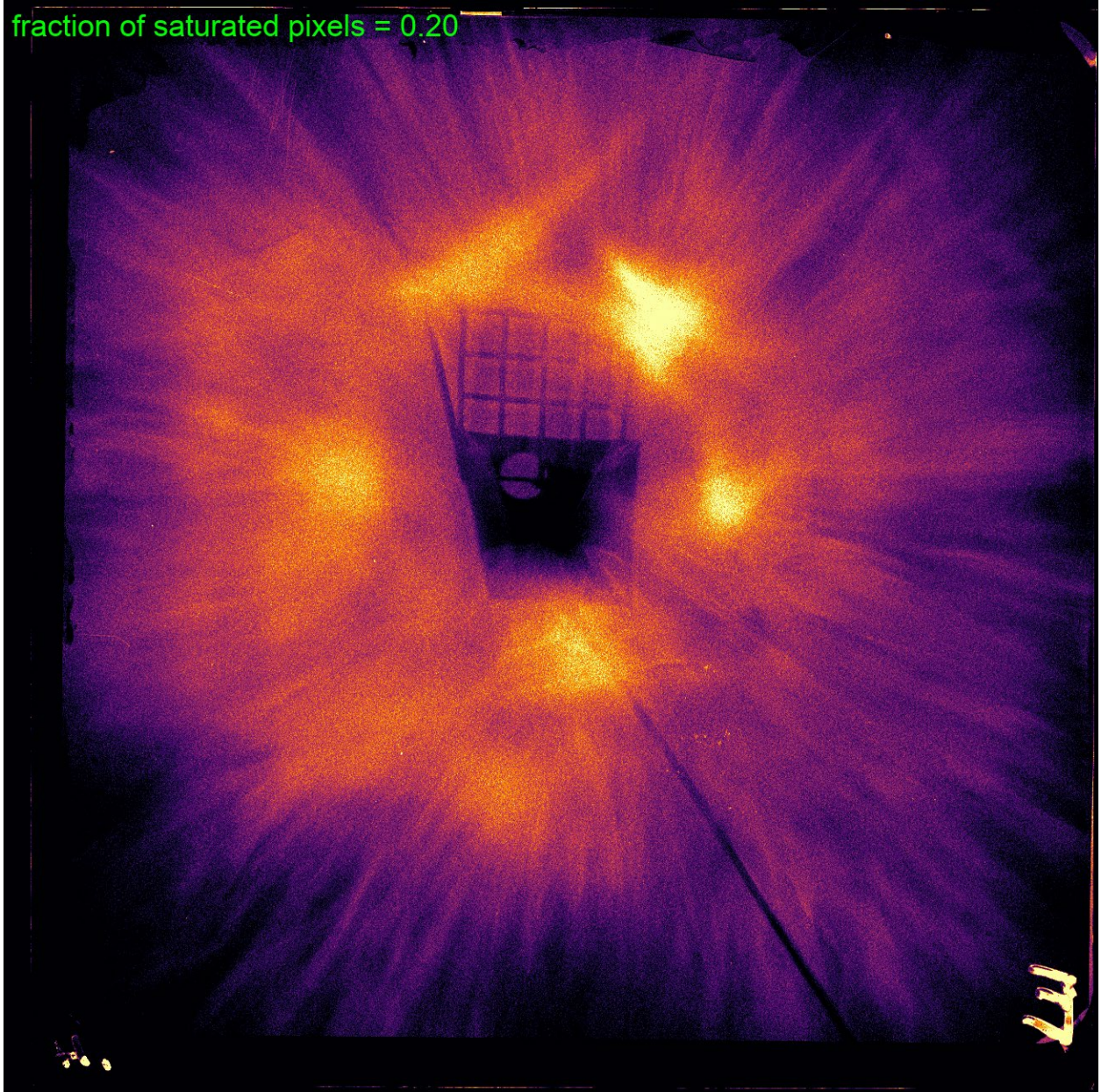


fraction of saturated pixels = 0.16

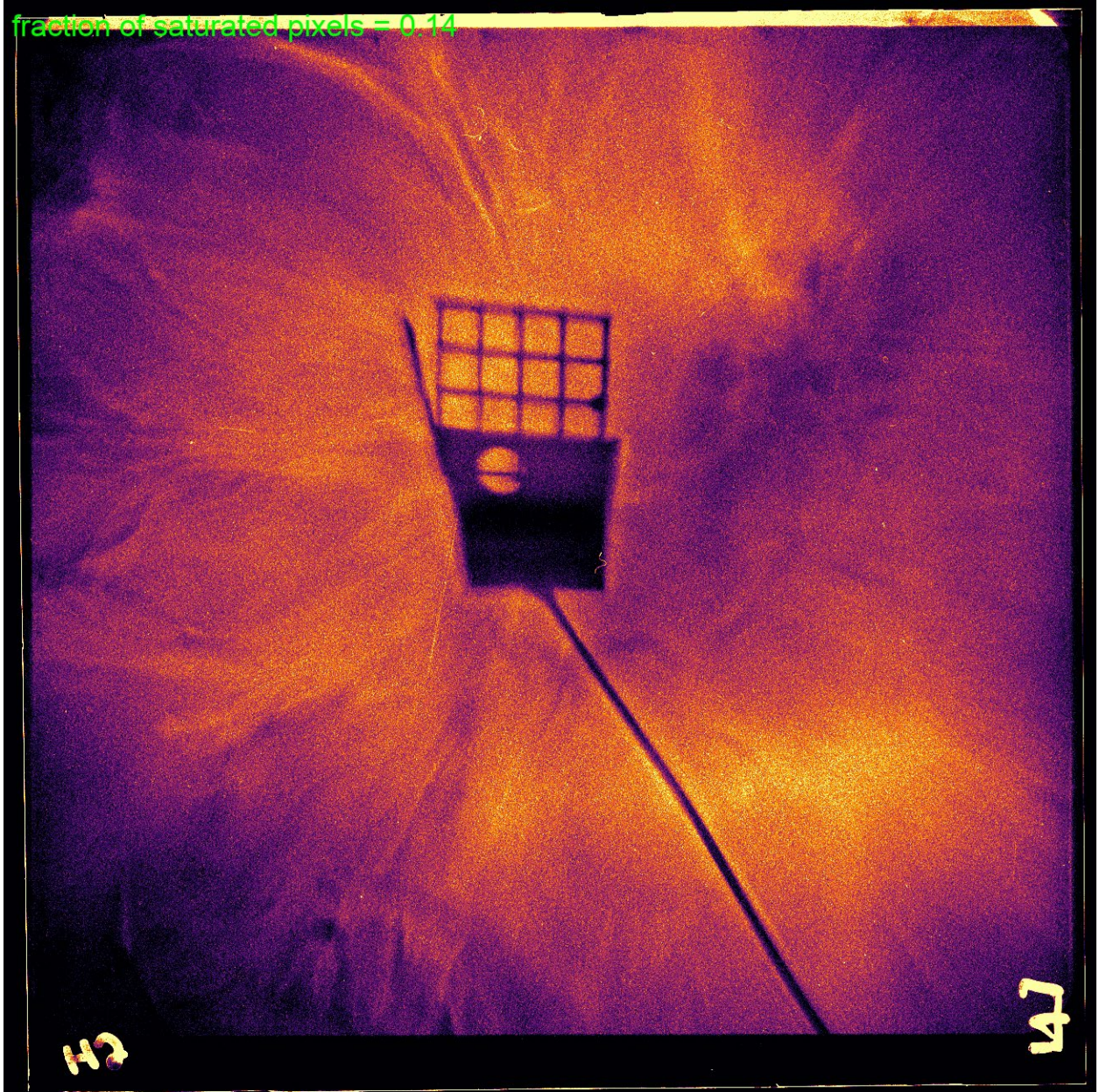


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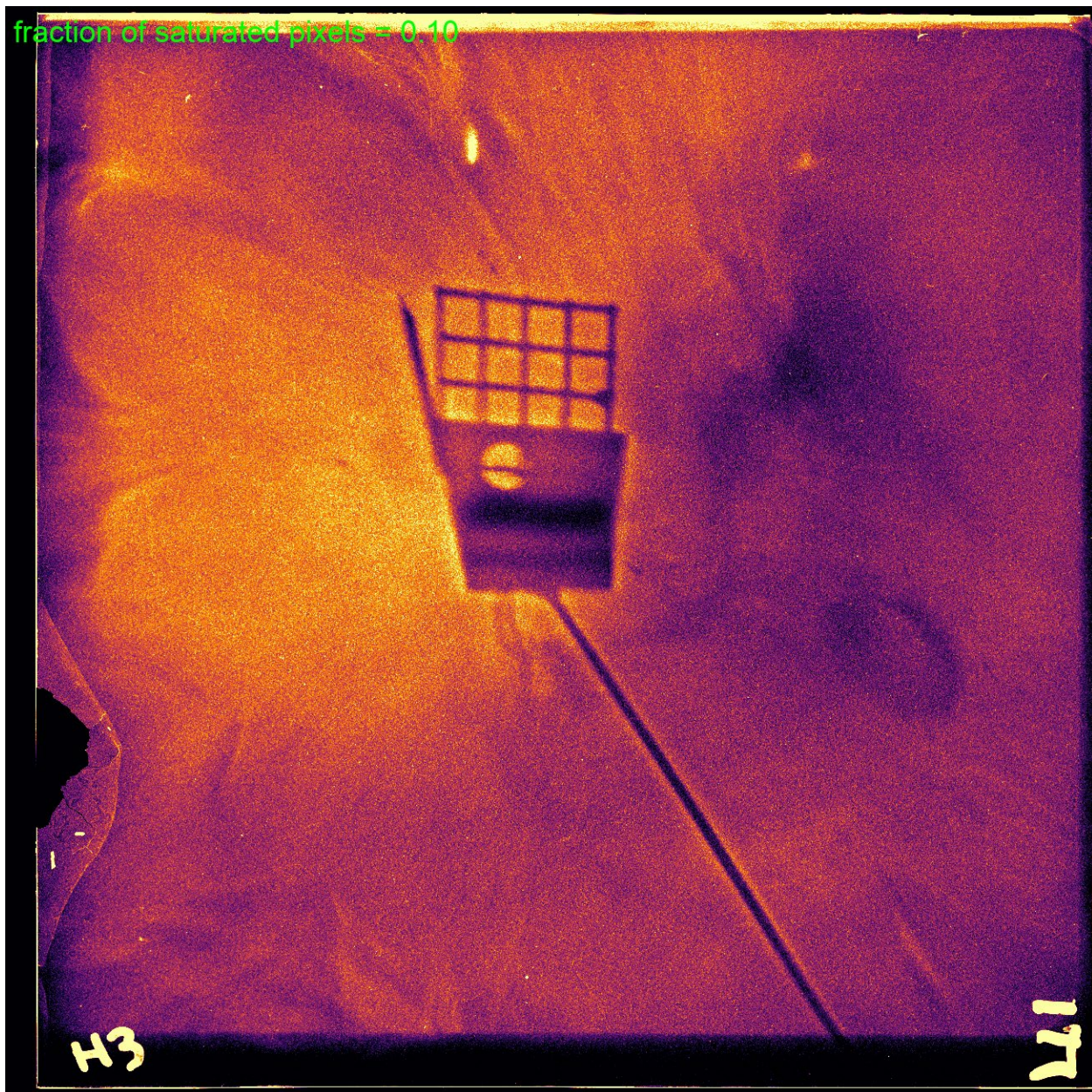
fraction of saturated pixels = 0.20



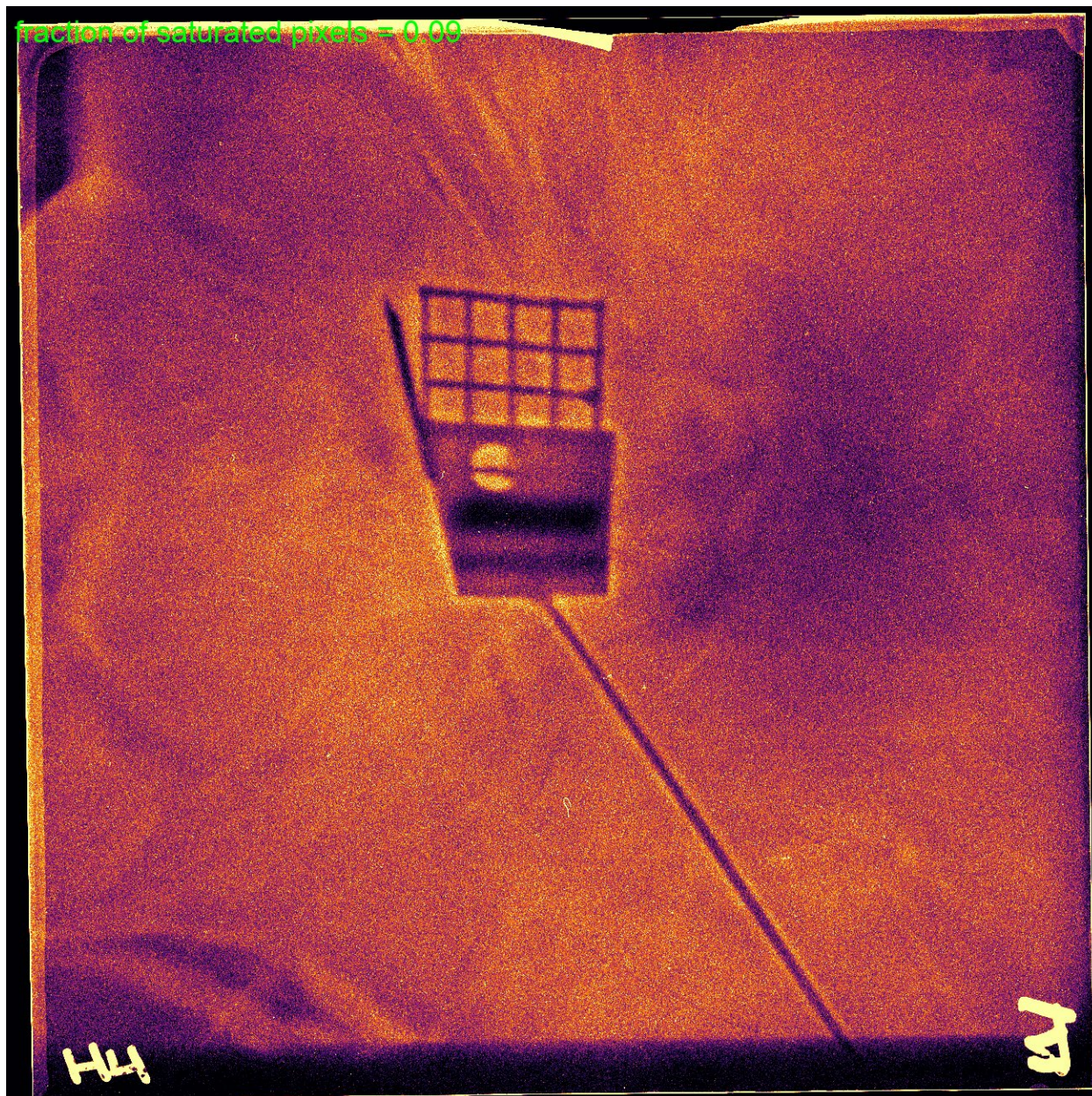
fraction of saturated pixels = 0.14



fraction of saturated pixels = 0.10



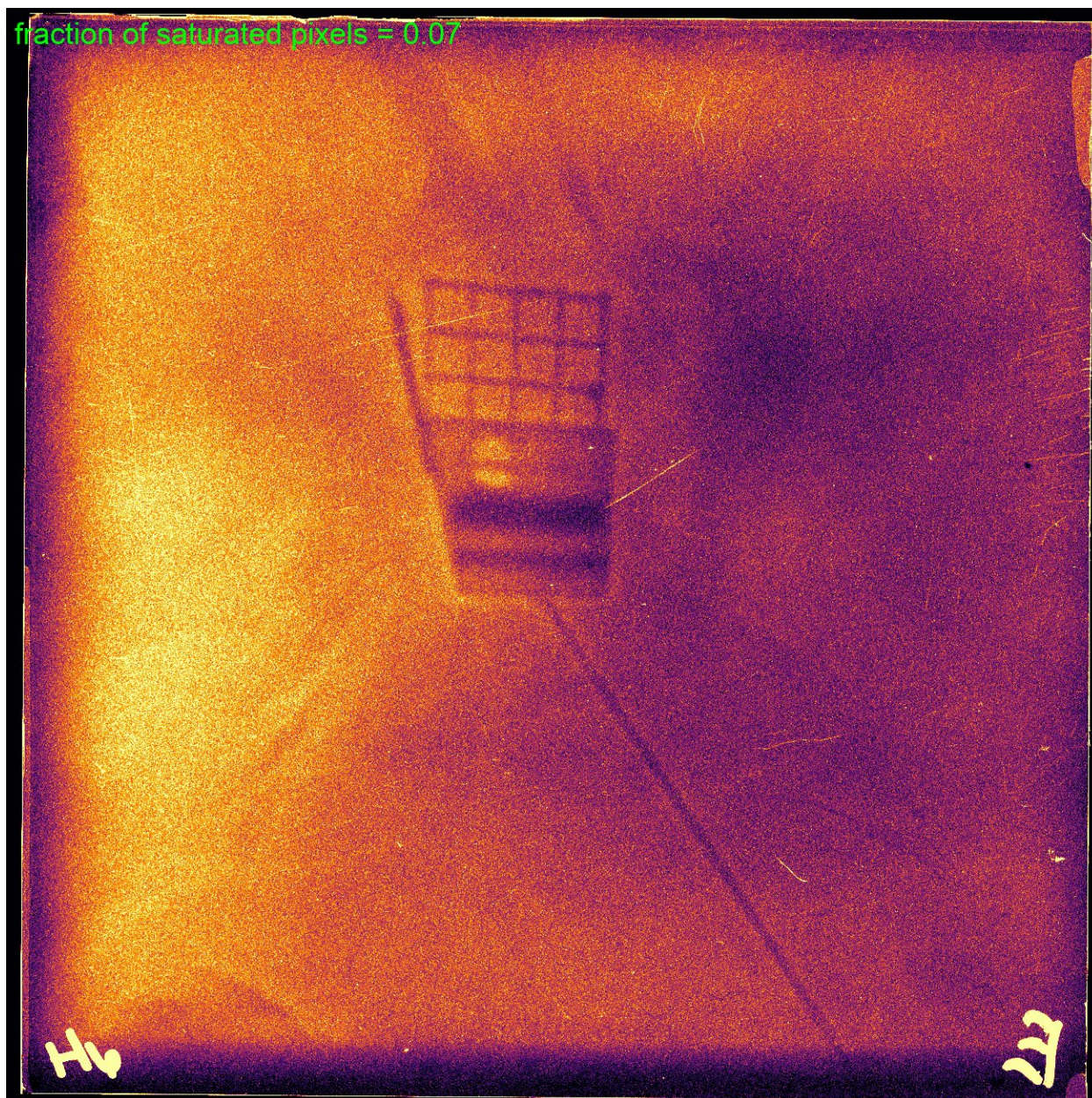
fraction of saturated pixels = 0.09



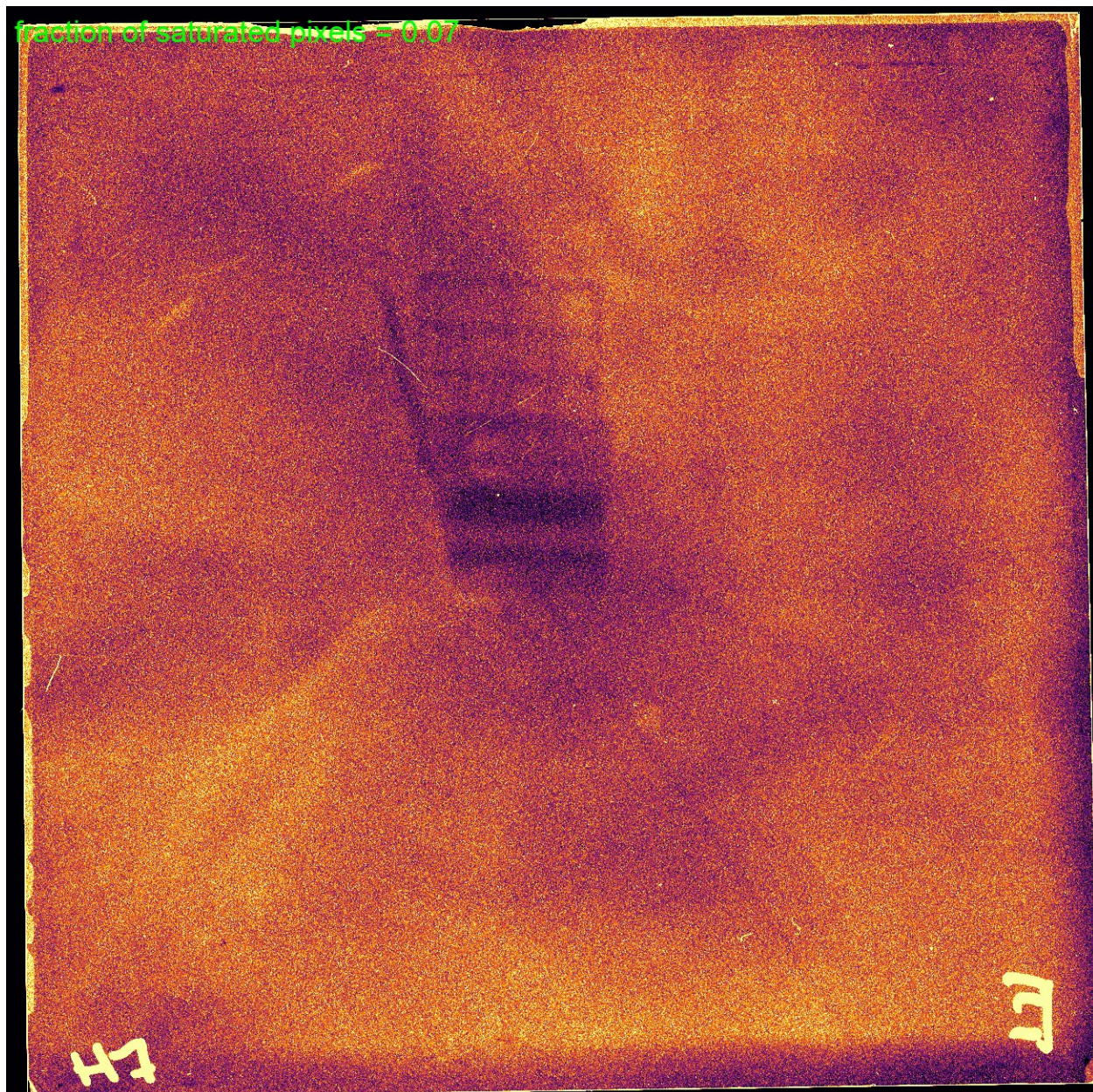
fraction of saturated pixels = 0.08



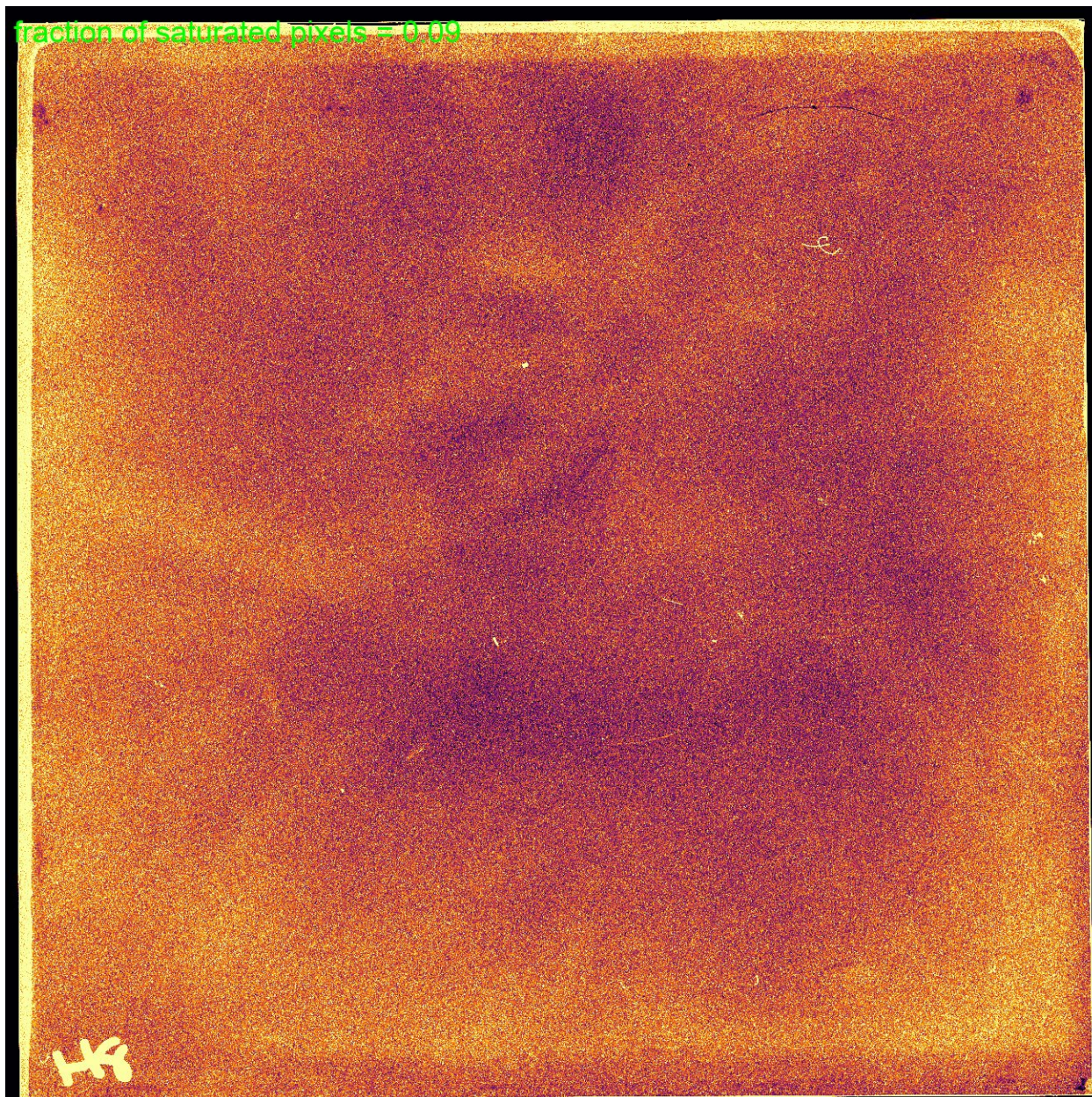
fraction of saturated pixels = 0.07

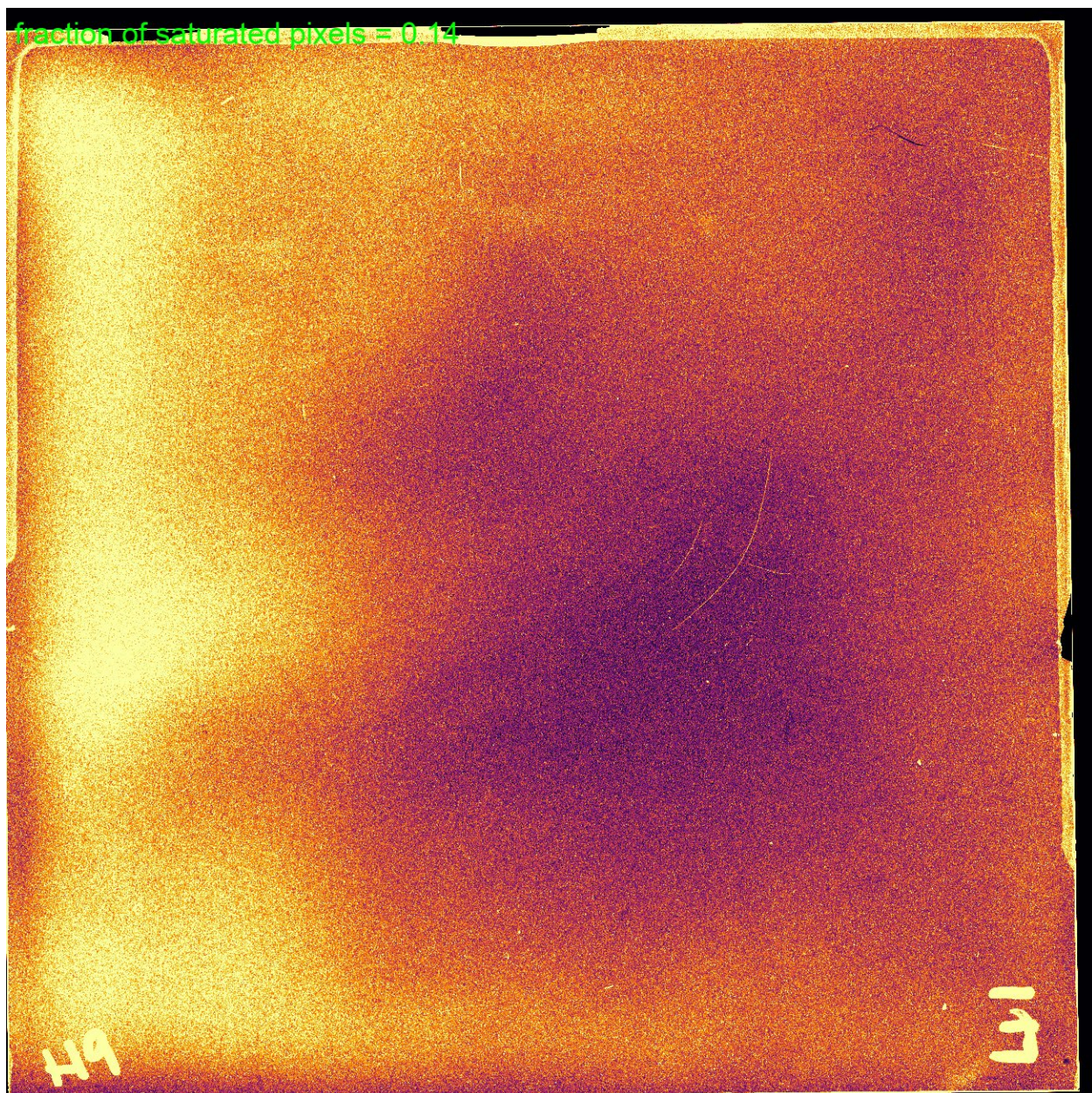


fraction of saturated pixels = 0.07



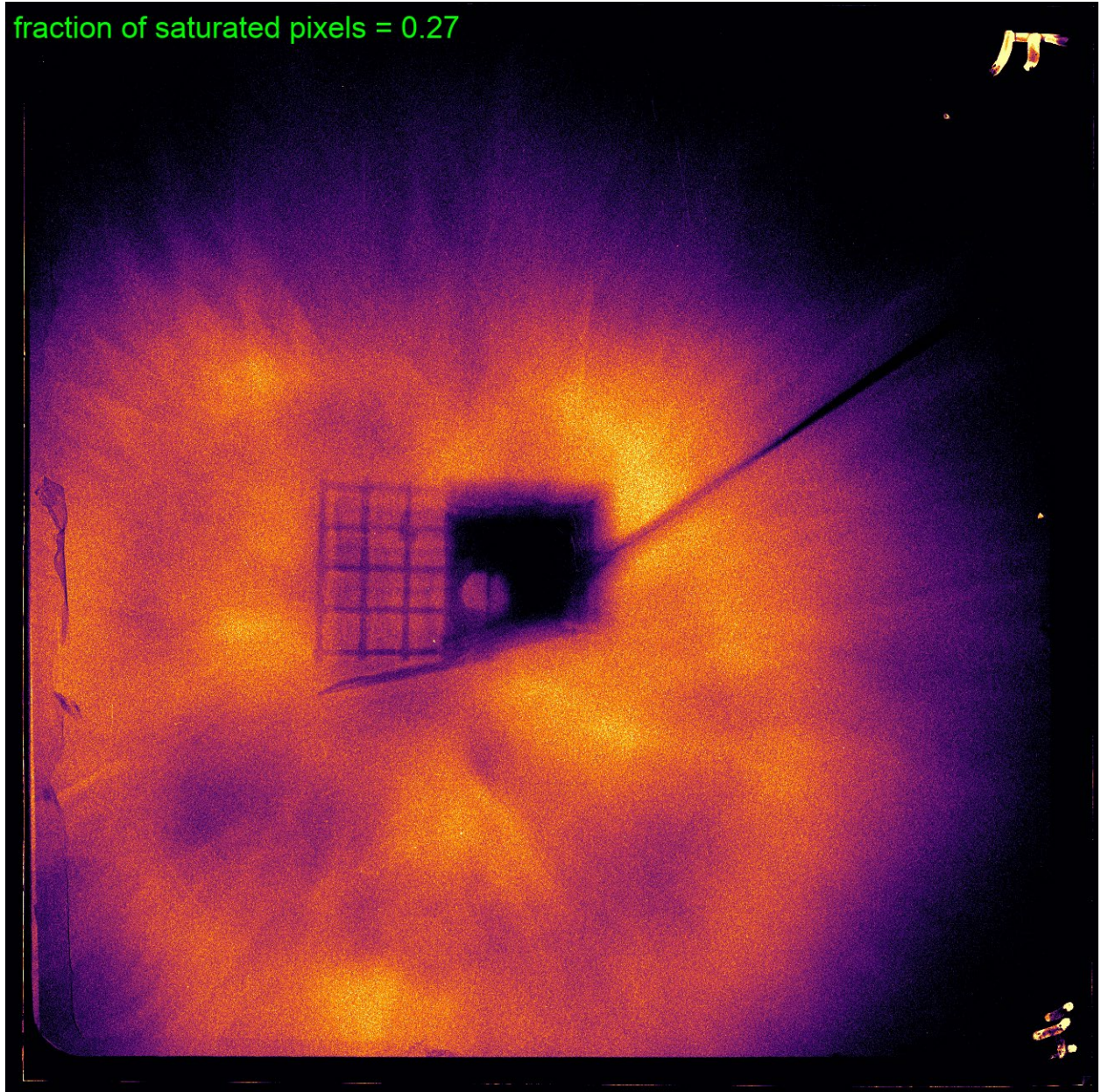
fraction of saturated pixels = 0.09





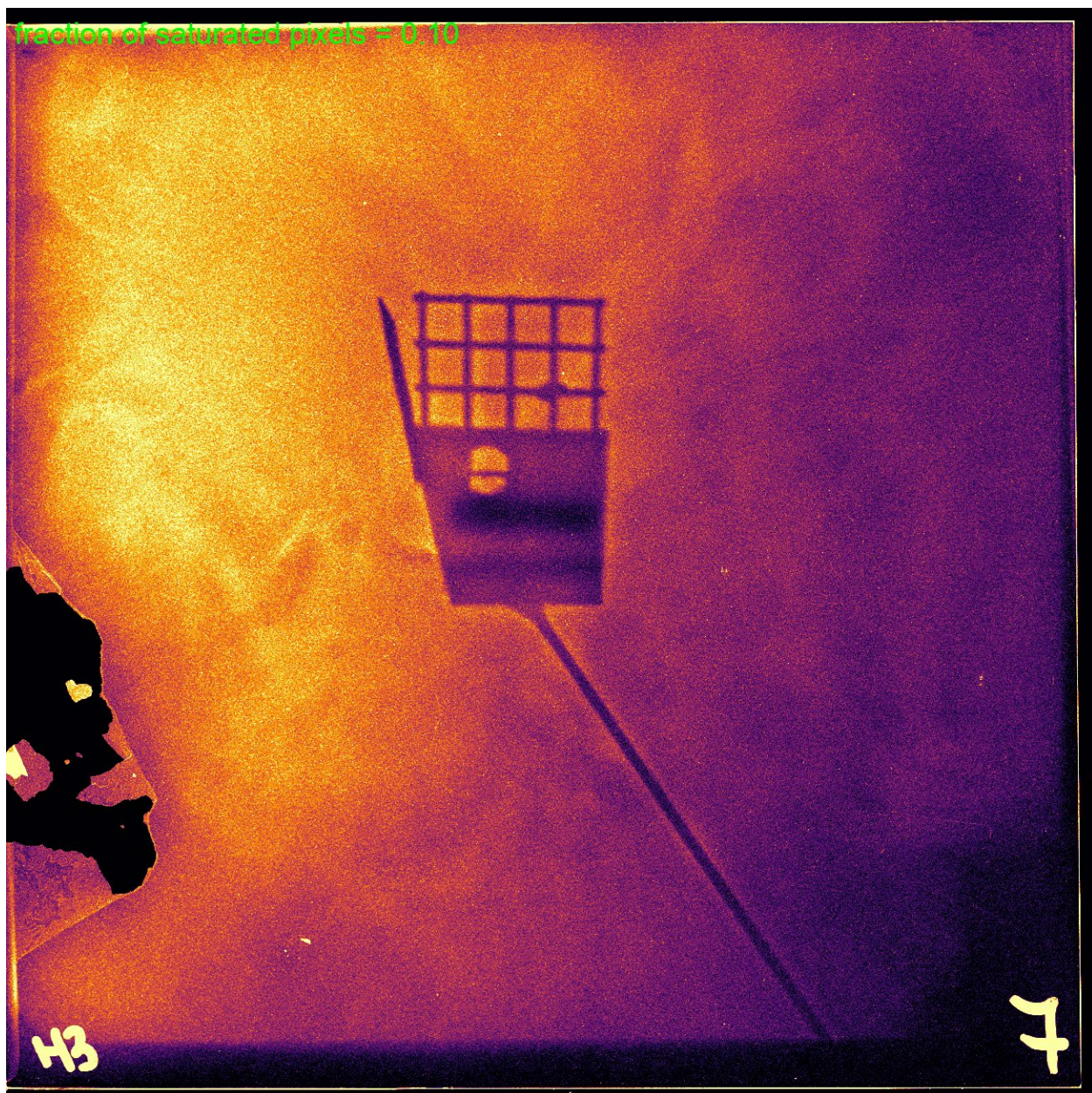
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fraction of saturated pixels = 0.27



fraction of saturated pixels = 0.17

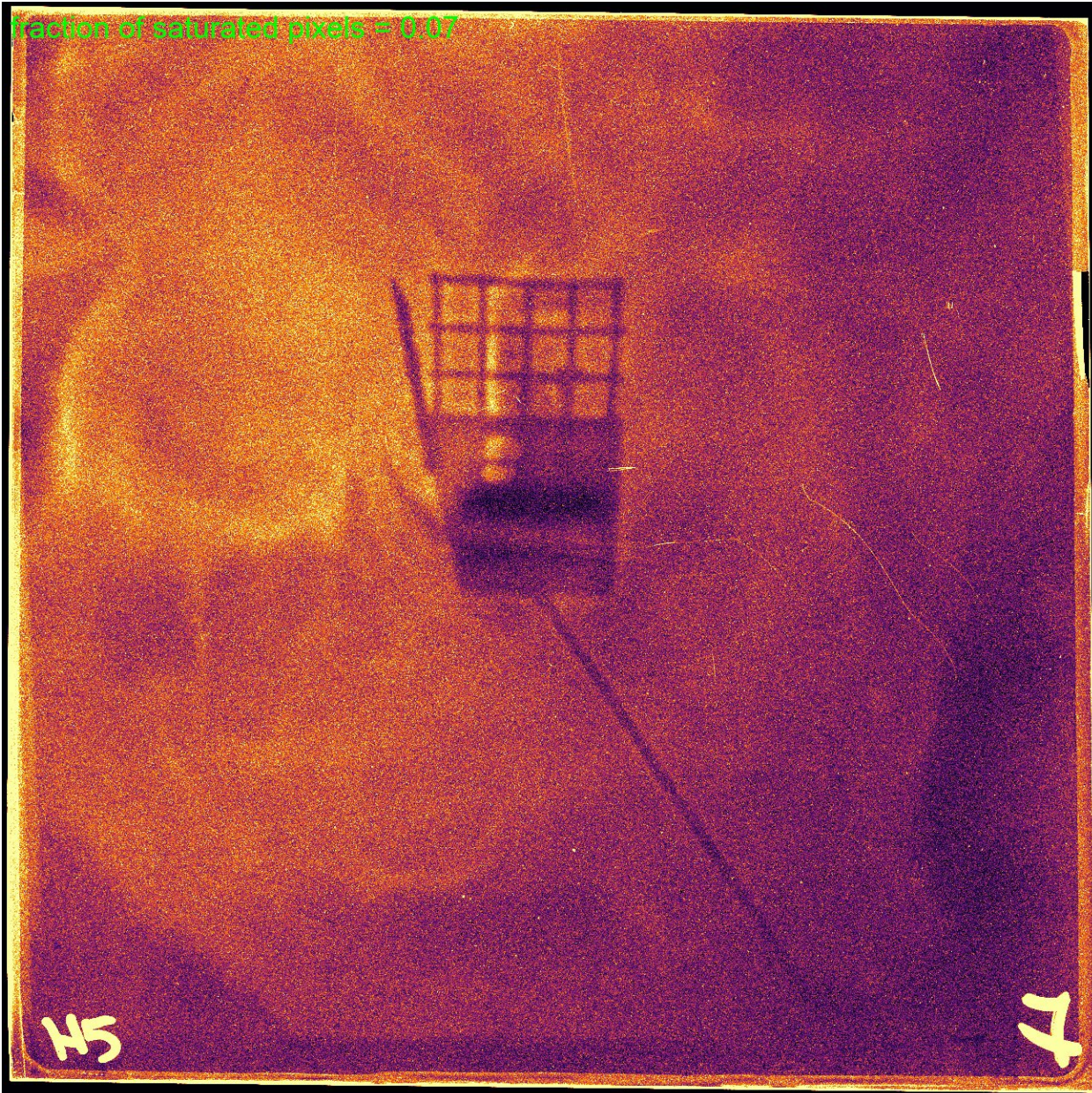




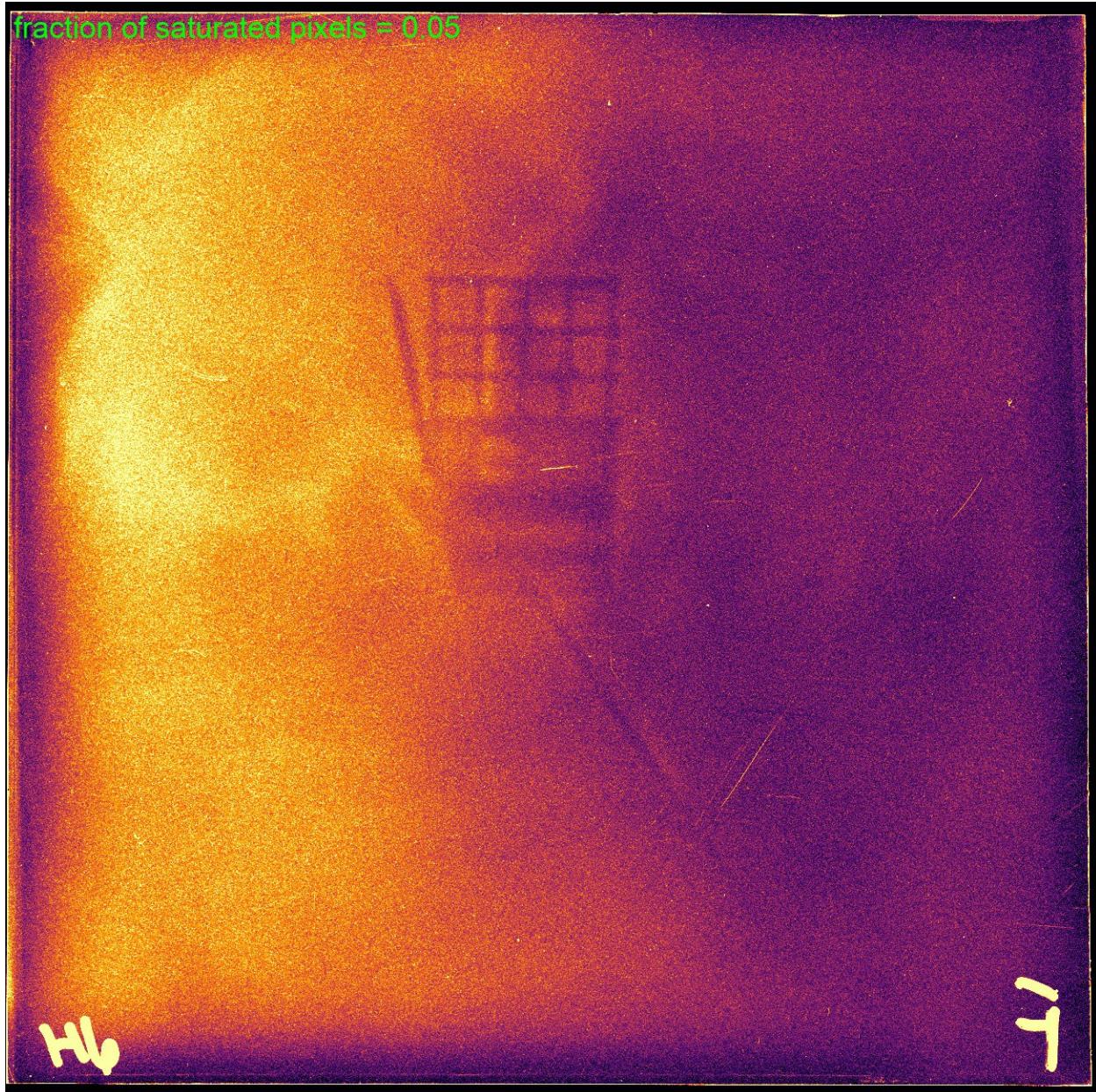
fraction of saturated pixels = 0.09

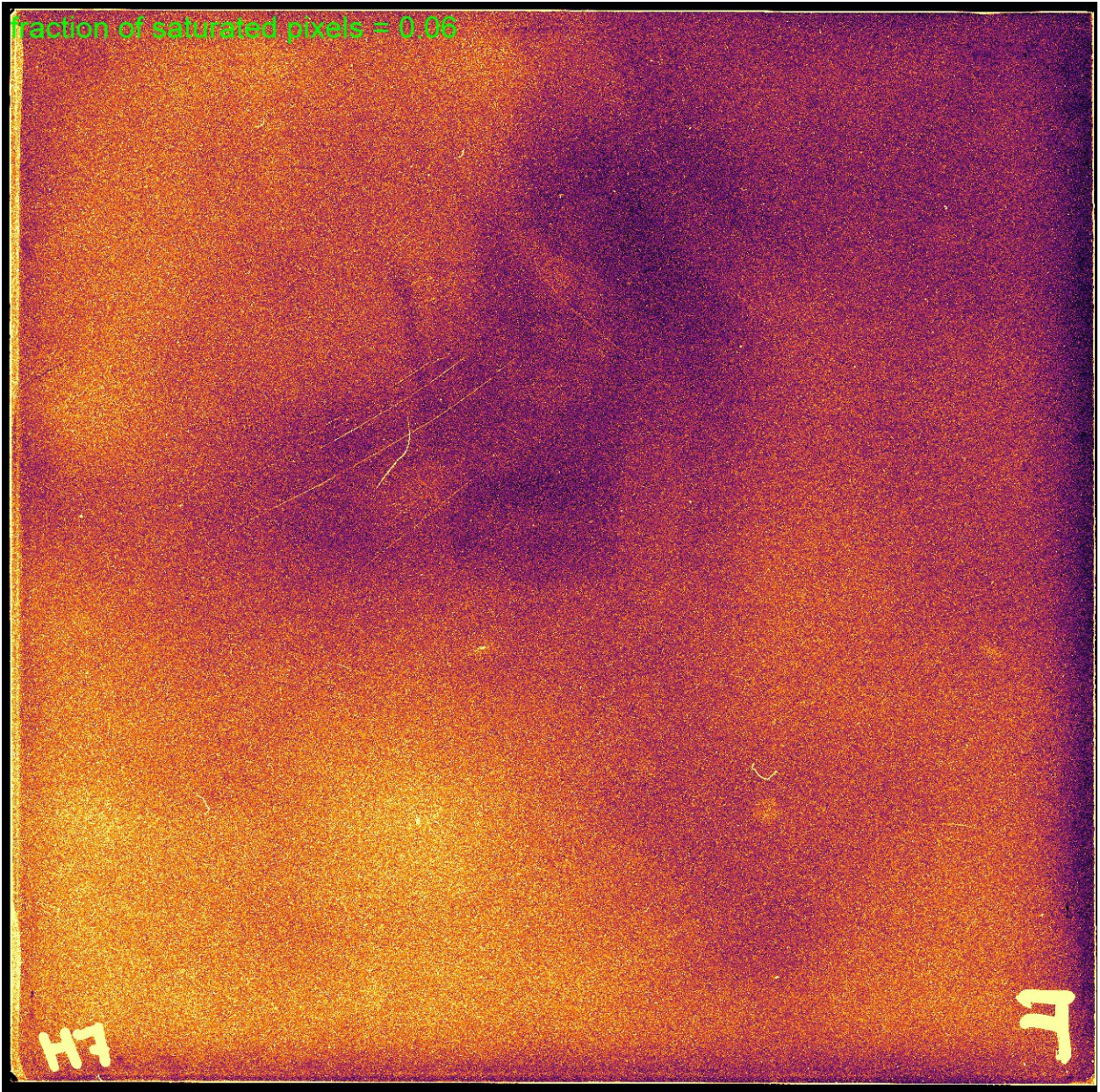


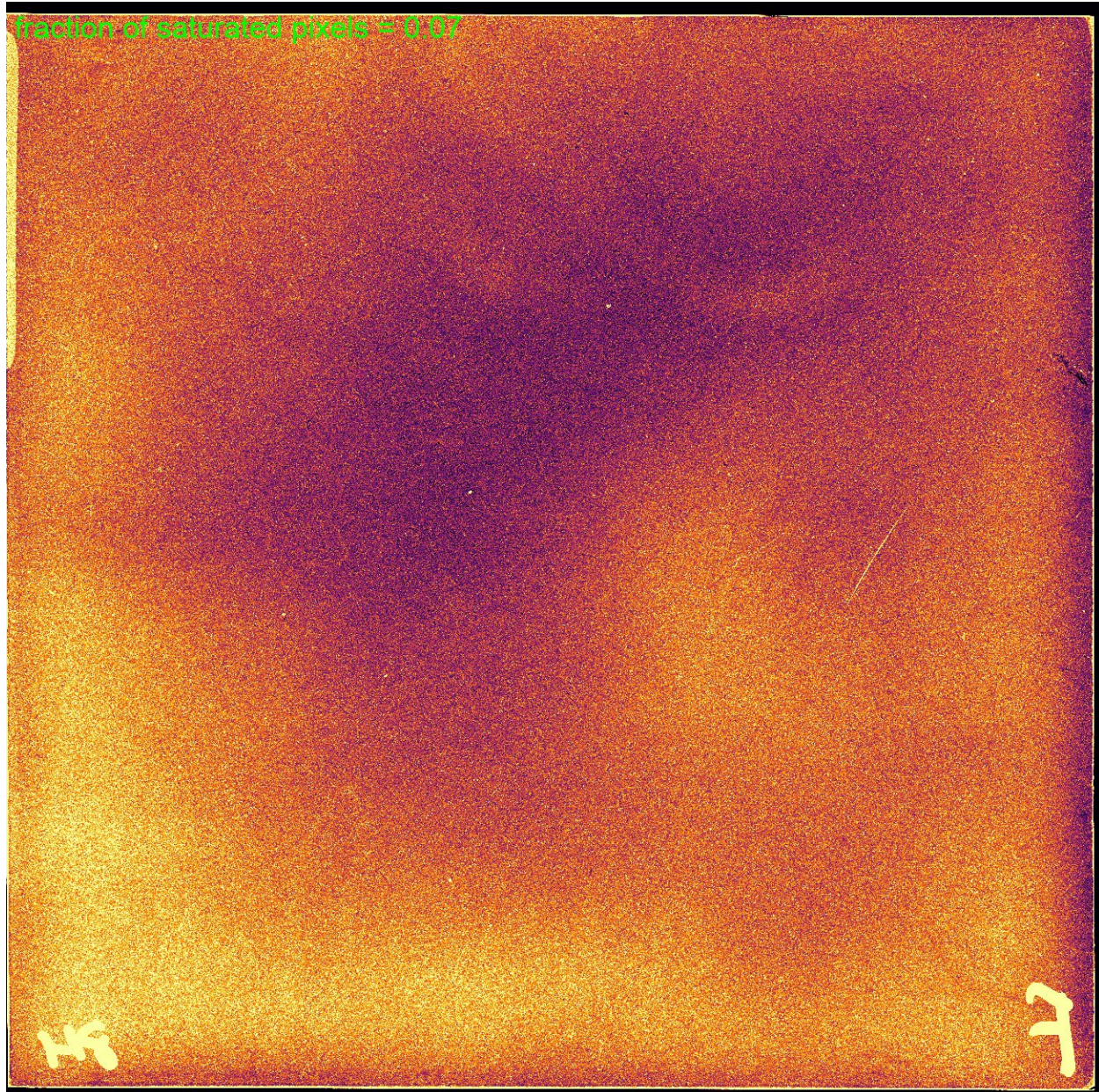
fraction of saturated pixels = 0.07



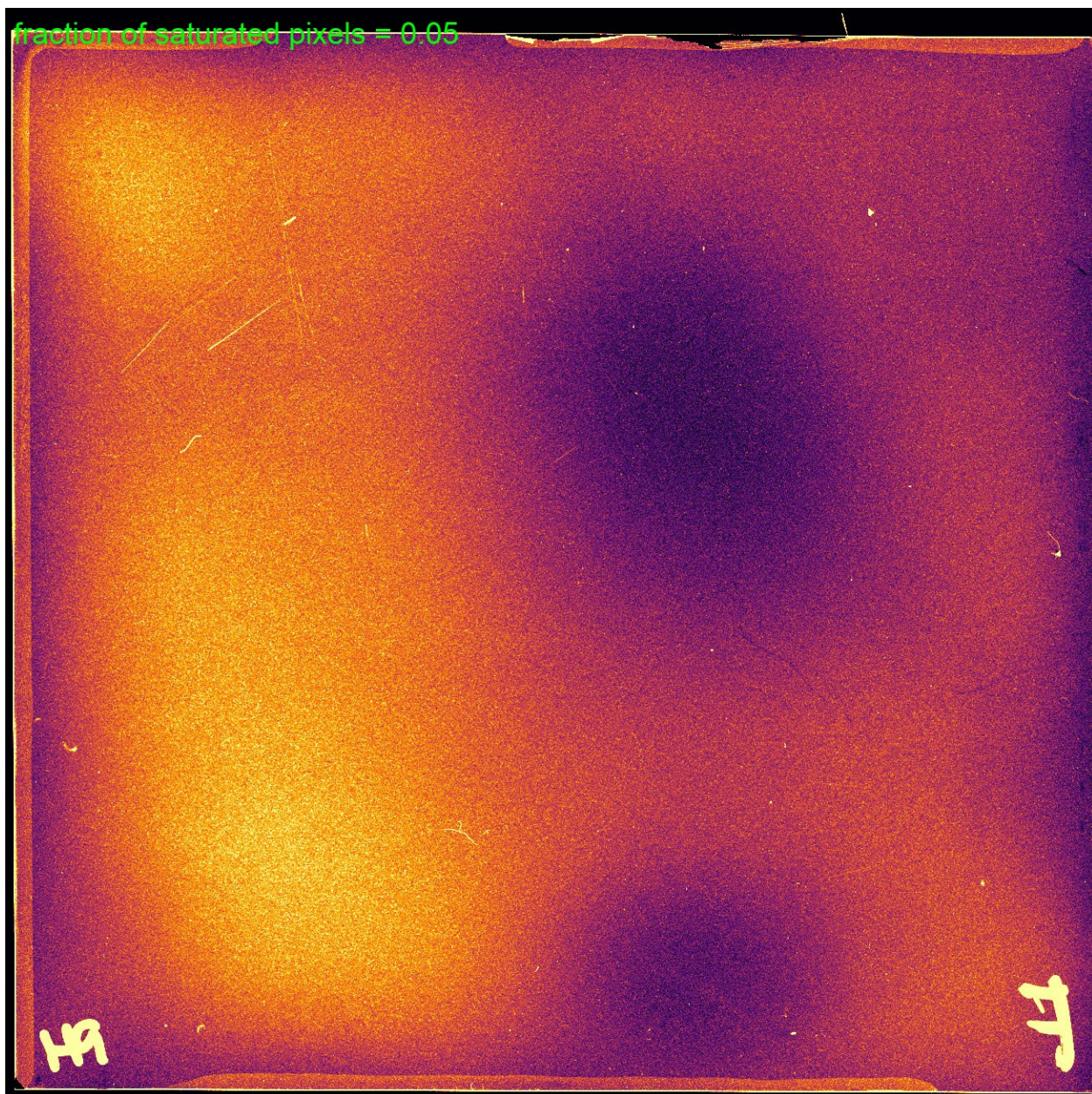
fraction of saturated pixels = 0.05





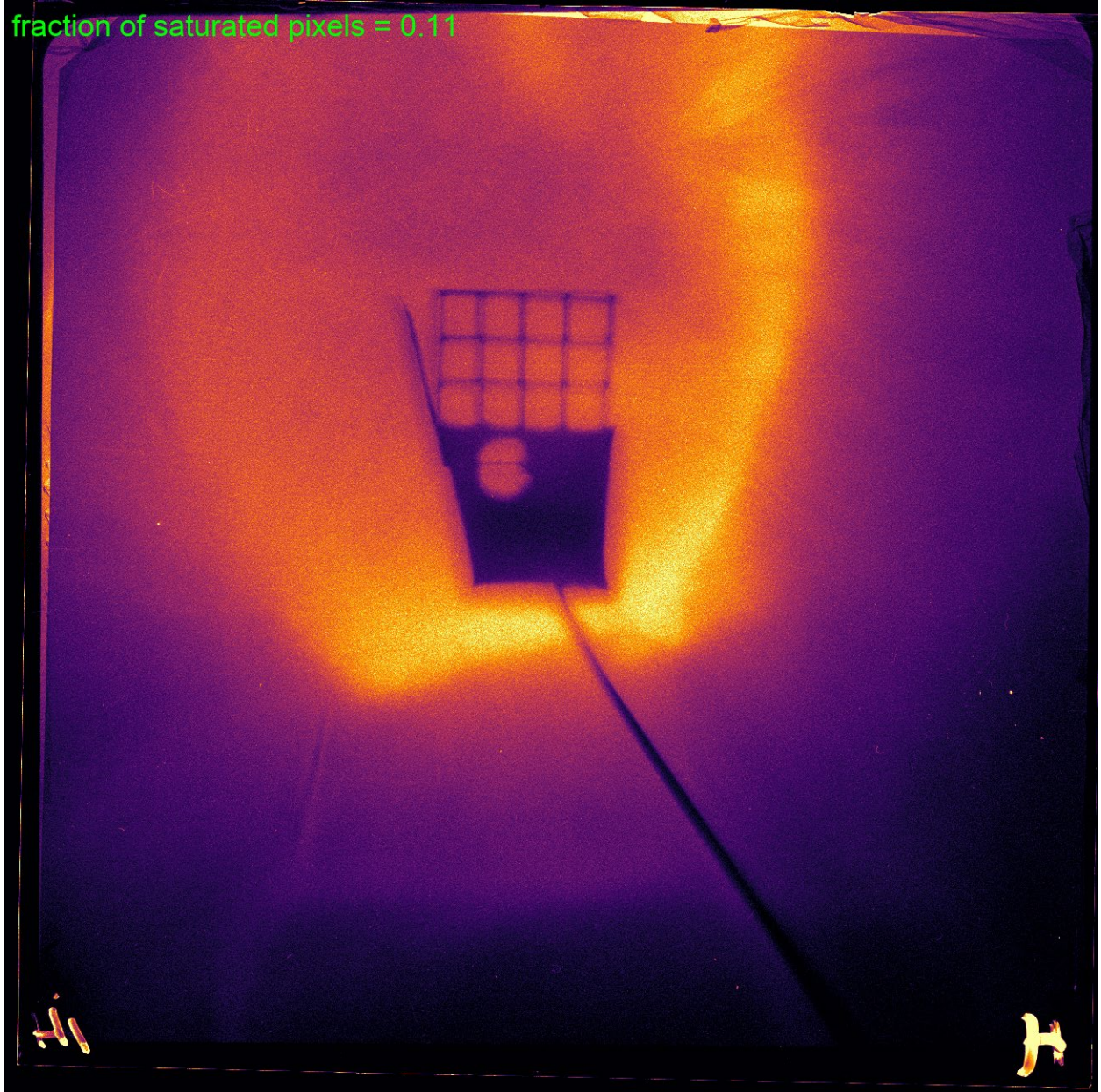


fraction of saturated pixels = 0.05



Shot 36442

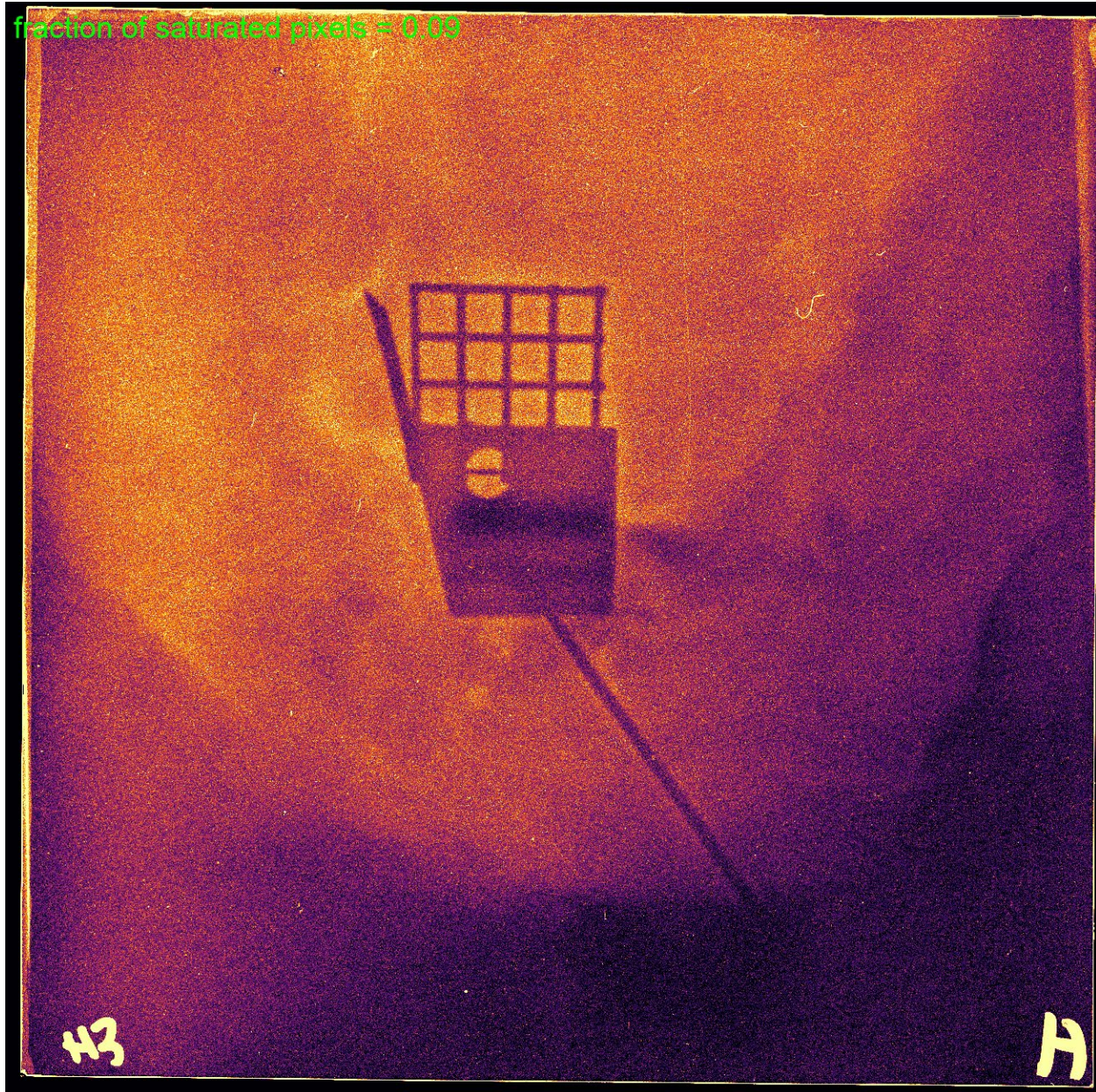
fraction of saturated pixels = 0.11



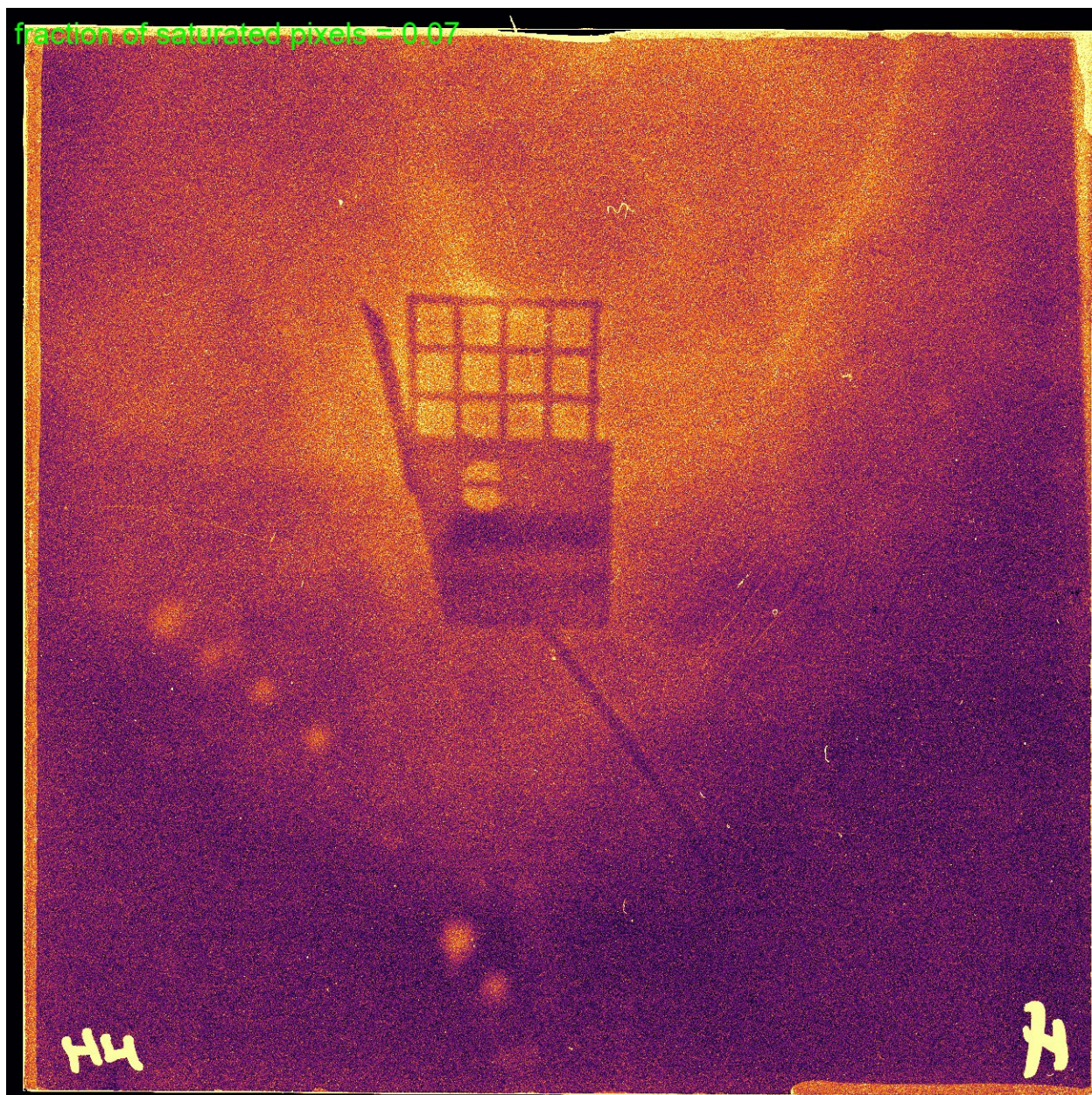
fraction of saturated pixels = 0.11



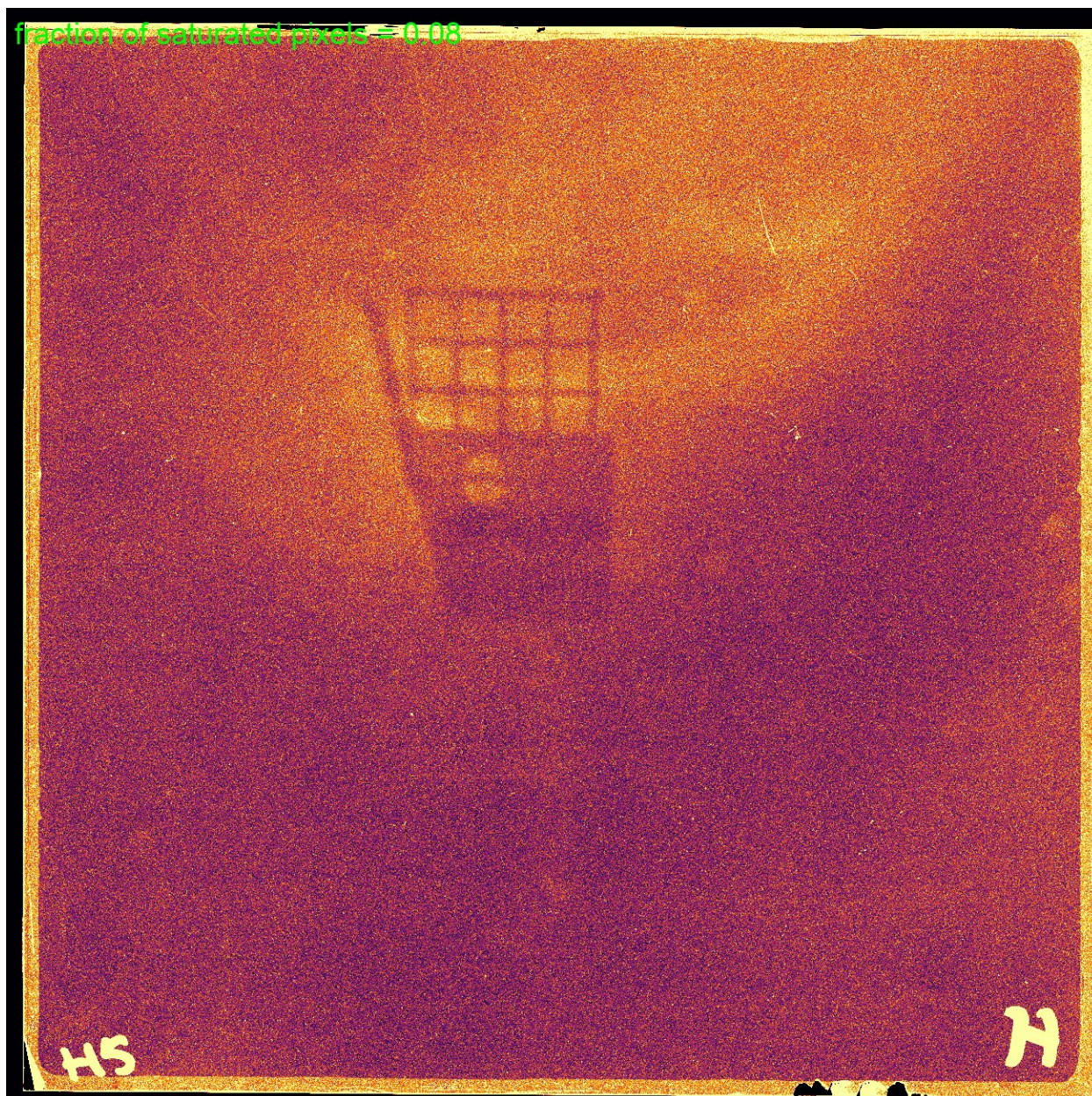
fraction of saturated pixels = 0.09



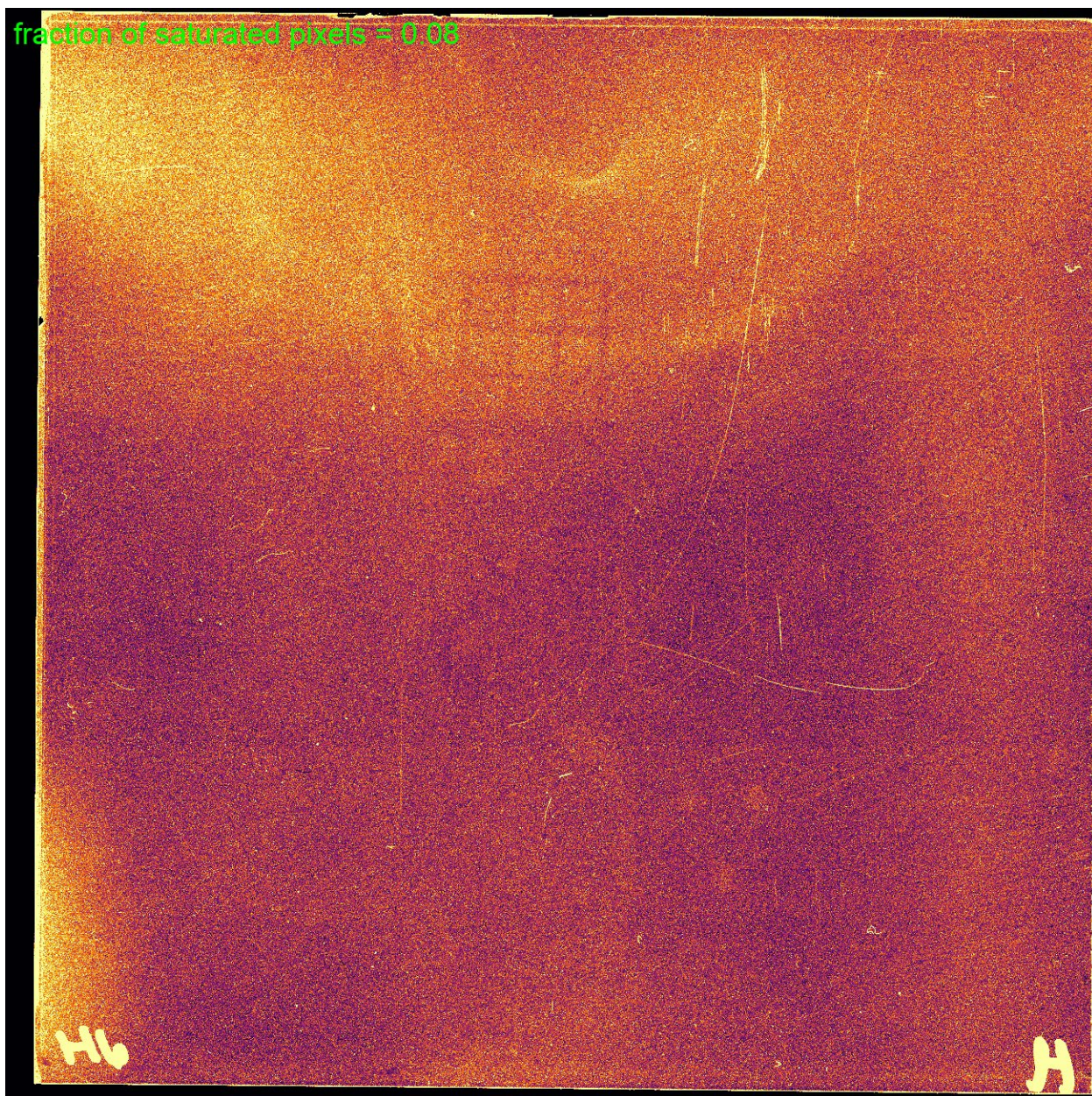
fraction of saturated pixels = 0.07



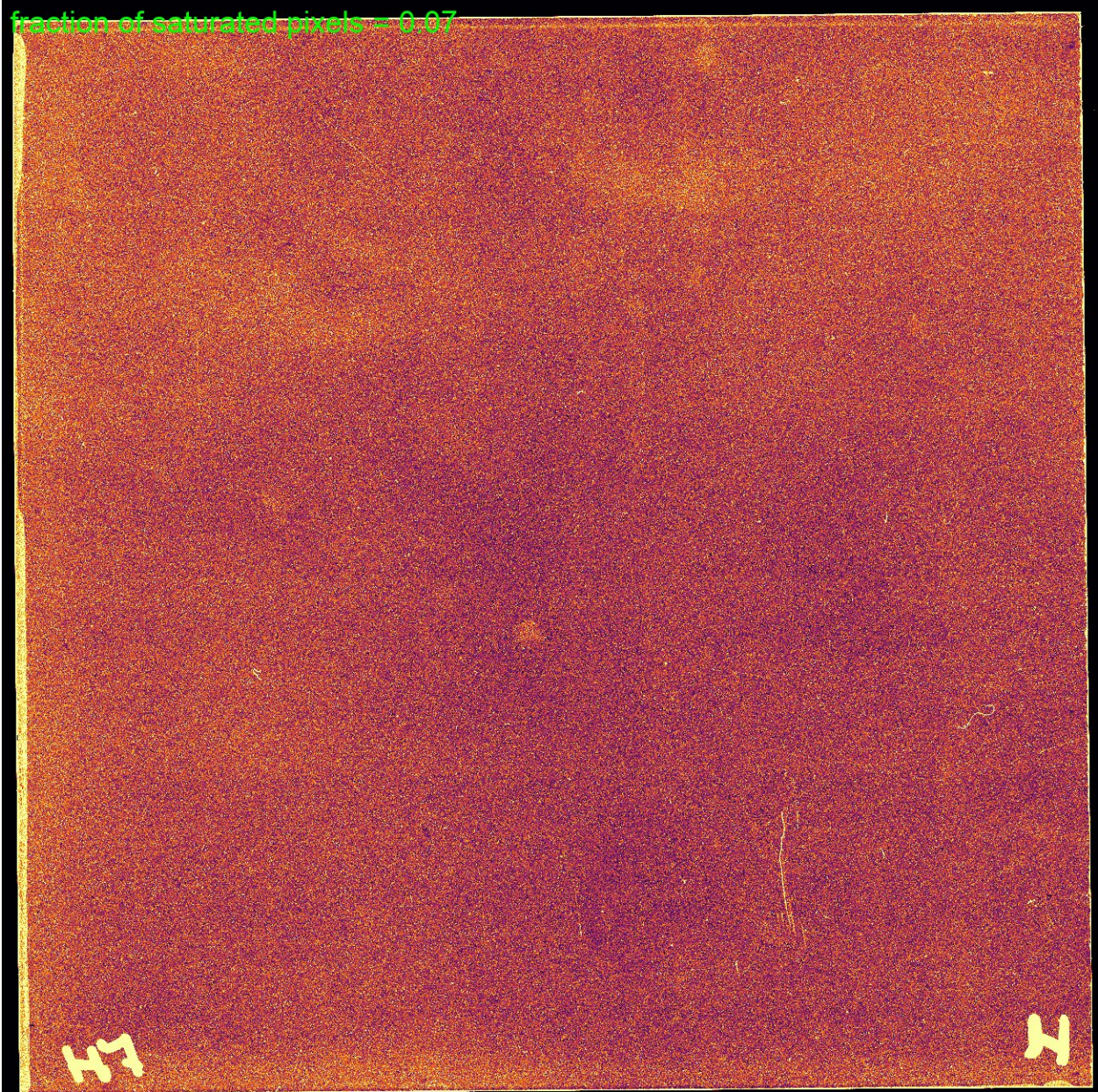
fraction of saturated pixels = 0.08



fraction of saturated pixels = 0.08

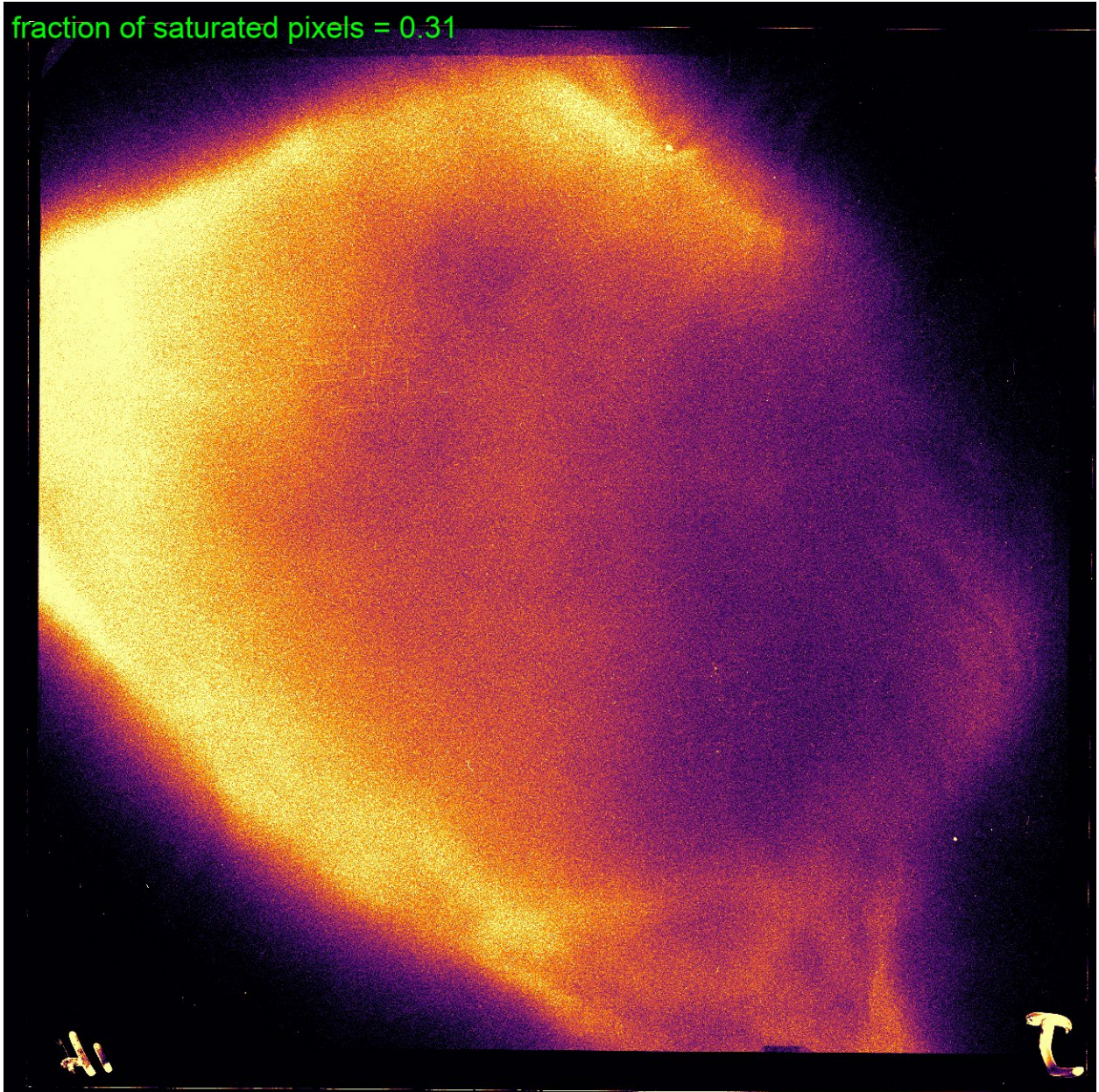


fraction of saturated pixels = 0.07

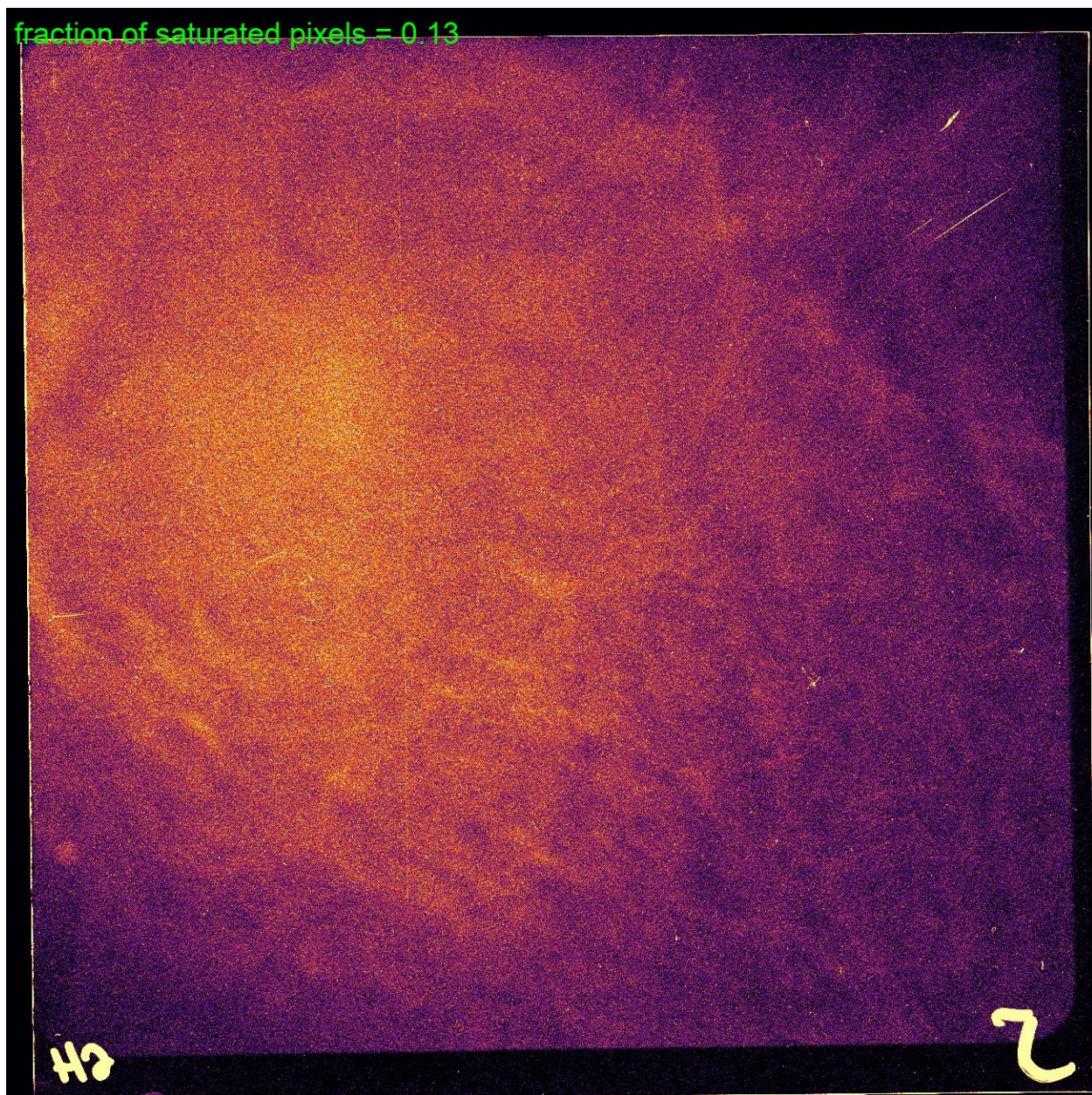


Shot 36444

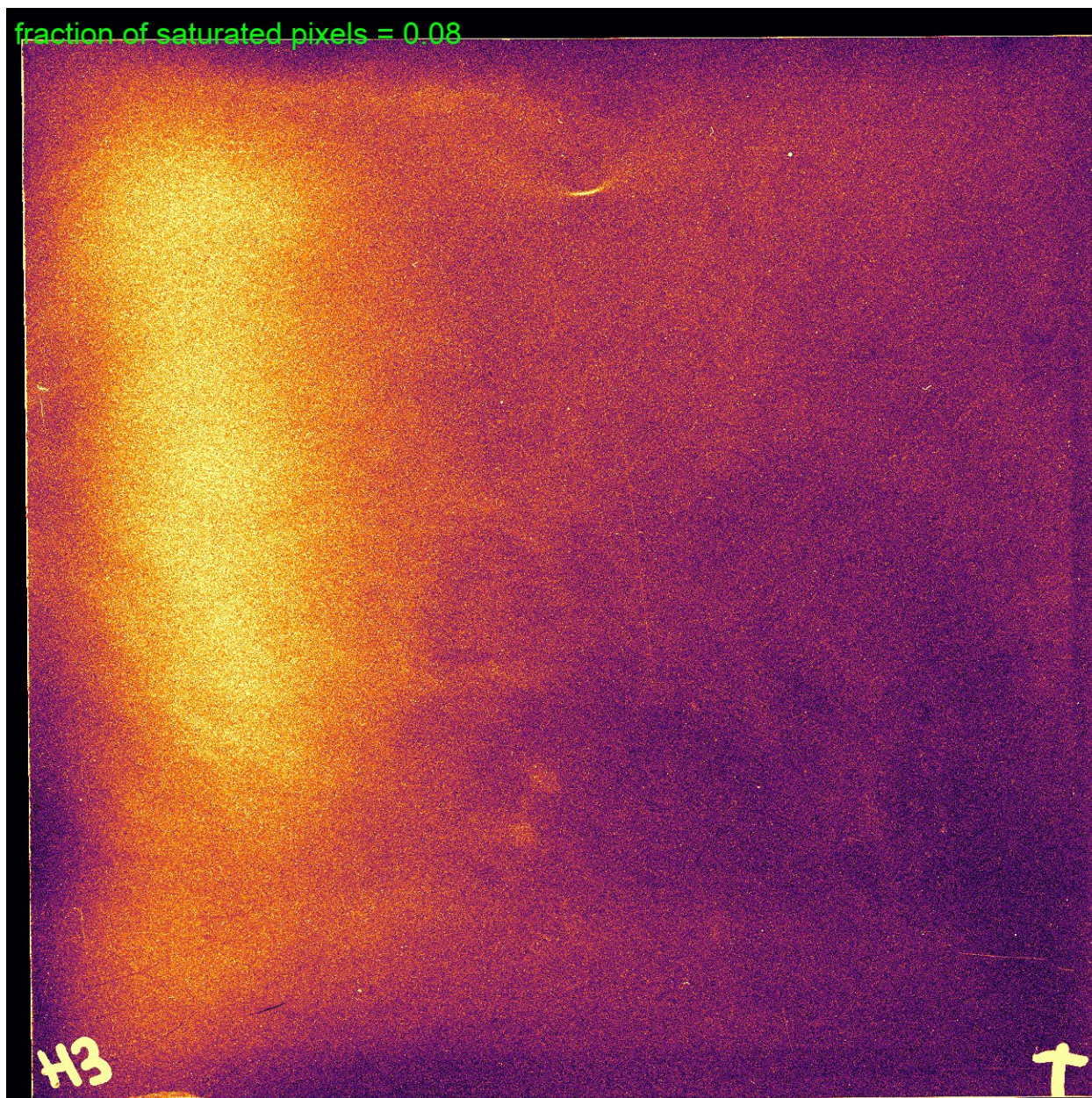
fraction of saturated pixels = 0.31



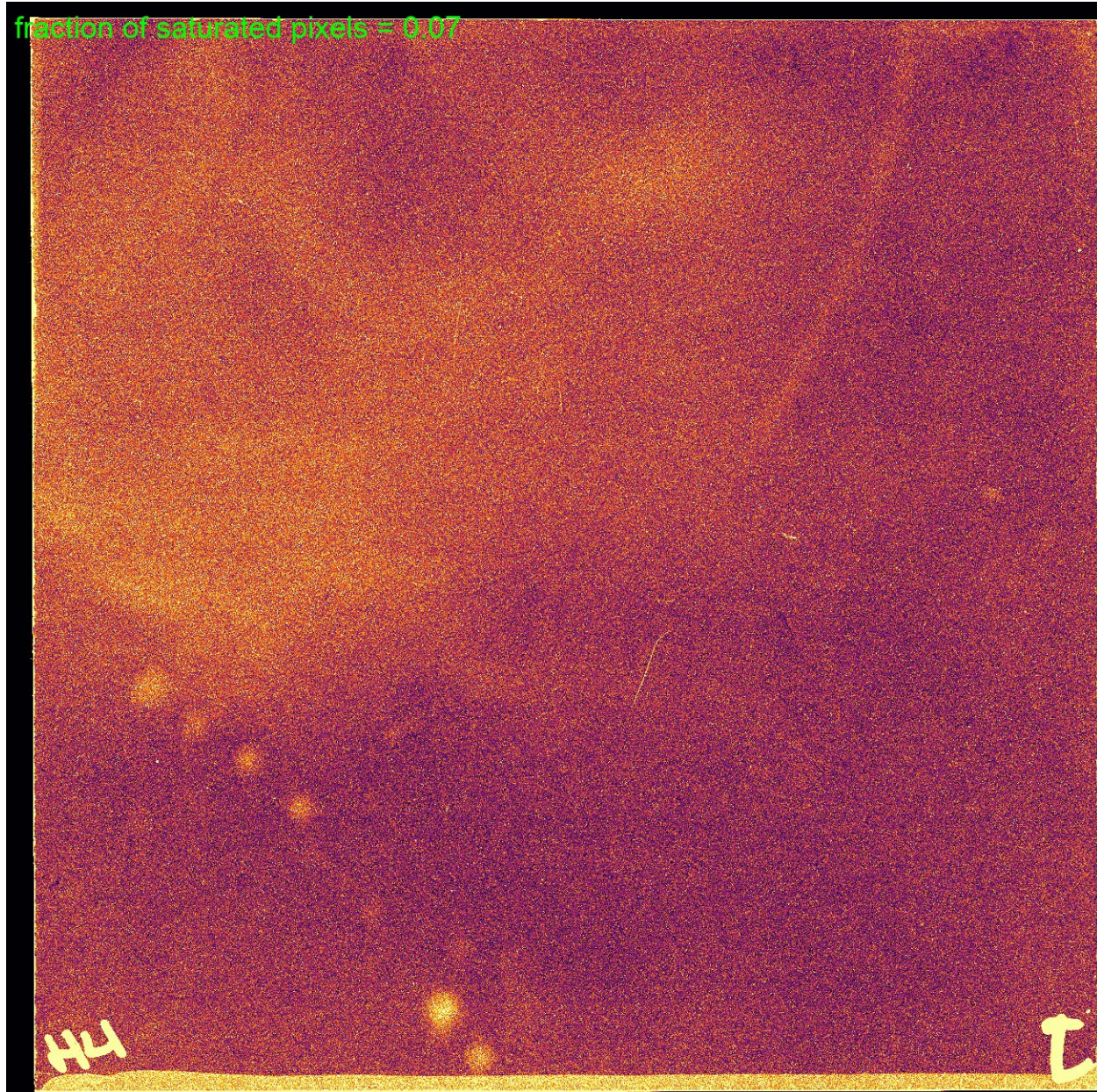
fraction of saturated pixels = 0.13



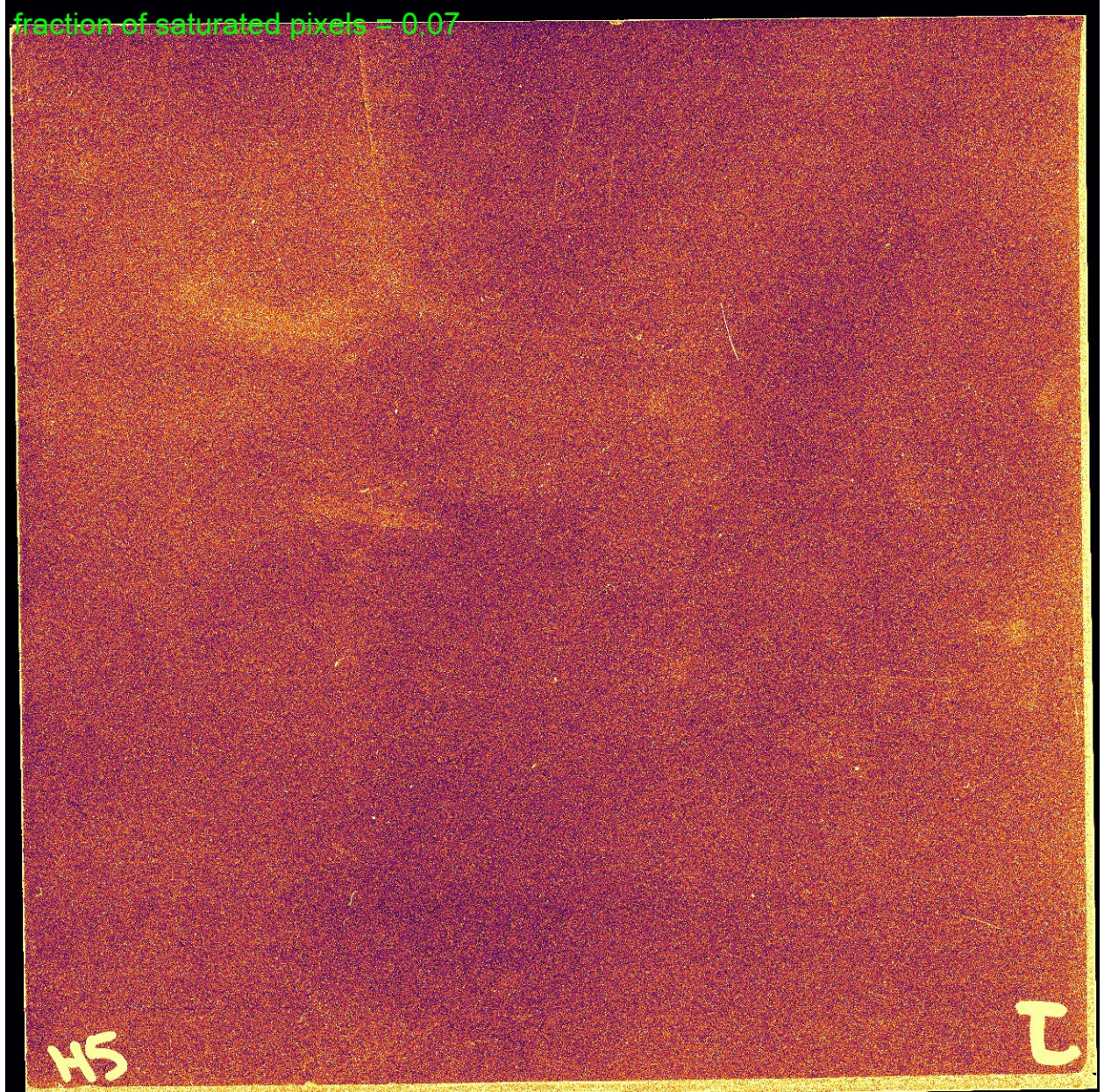
fraction of saturated pixels = 0.08



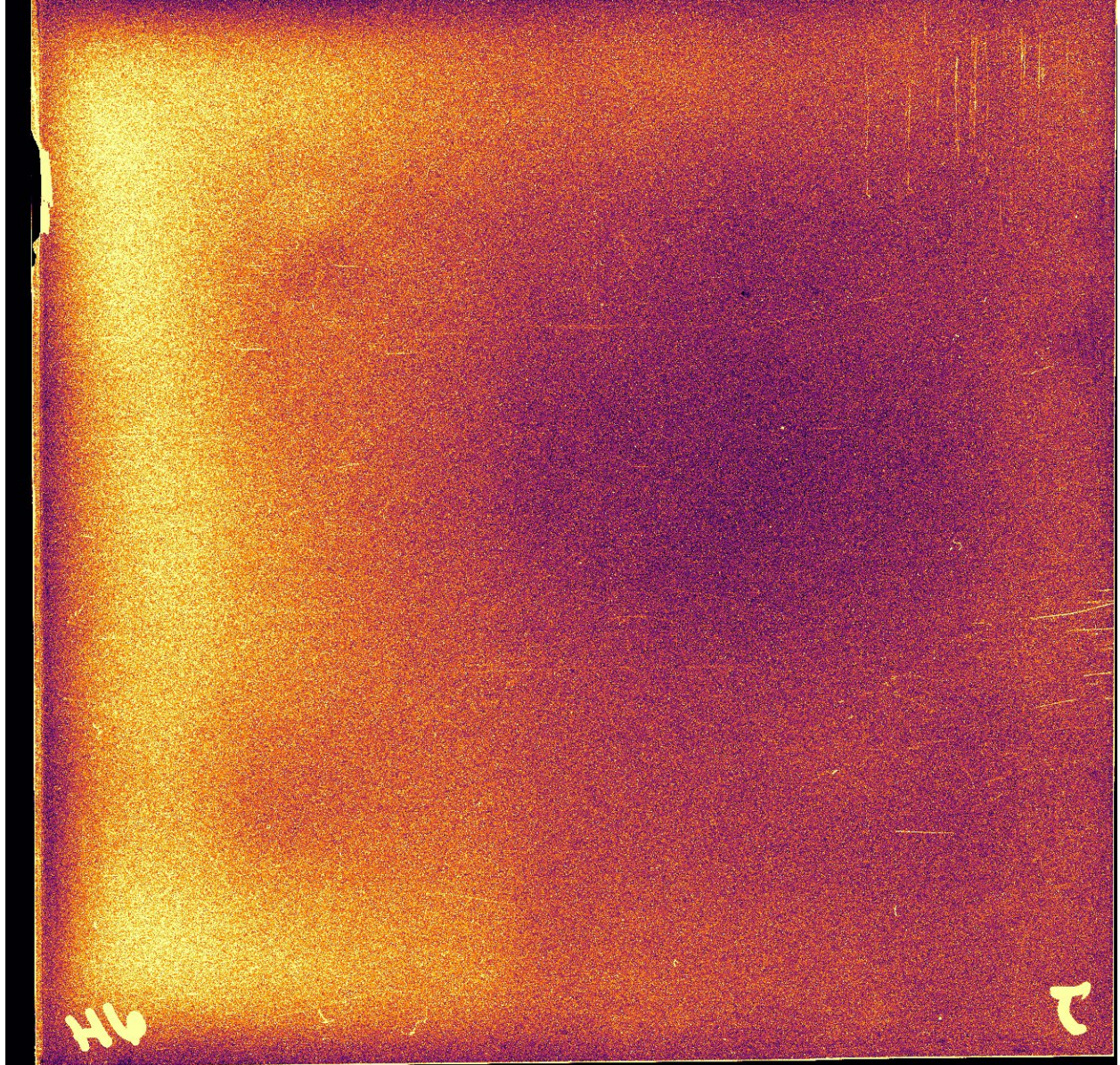
fraction of saturated pixels = 0.07



fraction of saturated pixels = 0.07



fraction of saturated pixels = 0.10



fraction of saturated pixels = 0.09

